CALIFORNIA ENERGY
COMMISSION

Costs & Savings For Houses Built With Ducts In Conditioned Space: Technical Information Report

Costs and Energy Savings for Homes with Ducts in Conditioned Space: Technical Information Package
(product 6.4.2e)

Building Code Official's Briefing Document: Variance for Attic Venting due to "Cathedralized" Attic
(product 6.4.2c)

TECHNICAL REPORT

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CALIFORNIA ENERGY COMMISSION

Prepared By:
GARD Analytics, Inc.
Roger Hedrick, Lead Author
Park Ridge, Illinois

Managed By:
New Buildings Institute
Cathy Higgins, ***Program Director***
White Salmon, Washington
CEC Contract No. 400-99-013

Prepared For:
Donald Aumann,
Contract Manager

Nancy Jenkins,
PIER Buildings Program Manager

Terry Surles,
PIER Program Director

Robert L. Therkelsen
Executive Director

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Project Director: Roger Hedrick, GARD Analytics, Inc.

Technical Assistance: Geof Syphers of XENERGY, Rob Hammon, Steve Vang and Bruce Baccei of ConSol, Bill Irvine of BCI Testing. Additional technical review by Alan Cowan of New Buildings Institute.

Review and Advisory Committee: Rick Chitwood of Chitwood Energy Management, Iain Walker of Lawrence Berkeley National Laboratory, Joe Lstiburek of Building Science Corporation, Bruce Wilcox of Berkeley Solar Group, Jamie Lyons of Energetics, Inc., Marshall Hunt of Pacific Gas & Electric.

Project Management: Cathy Higgins, Program Director for New Buildings Institute, and Don Aumann, Contract Manager for the California Energy Commission.

PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

This document is one of 33 technical attachments to the final report of a larger research effort called *Integrated Energy Systems: Productivity and Building Science Program* (Program) as part of the PIER Program funded by the California Energy Commission (Commission) and managed by the New Buildings Institute.

As the name suggests, it is not individual building components, equipment, or materials that optimize energy efficiency. Instead, energy efficiency is improved through the integrated design, construction, and operation of building systems. The *Integrated Energy Systems: Productivity and Building Science Program* research addressed six areas:

- Productivity and Interior Environments
- Integrated Design of Large Commercial HVAC Systems
- Integrated Design of Small Commercial HVAC Systems
- Integrated Design of Commercial Building Ceiling Systems
- Integrated Design of Residential Ducting & Air Flow Systems
- Outdoor Lighting Baseline Assessment

The Program's final report (Commission publication #P500-03-082) and its attachments are intended to provide a complete record of the objectives, methods, findings and accomplishments of the *Integrated Energy Systems: Productivity and Building Science Program*. The final report and attachments are highly applicable to architects, designers, contractors, building owners and operators, manufacturers, researchers, and the energy efficiency community.

This attachment, "Costs & Savings for Houses Built with Ducts in Conditioned Space: Technical Information Report" (Attachment A-31) provides supplemental information to the final report within the **Integrated Design of Residential Ducting & Air Flow Systems** research area. It includes the following reports:

1. **Costs and Energy Savings for Homes with Ducts in Conditioned Space: Technical Information Package.** This describes the estimates of construction cost impacts and energy savings for houses built in California with ducts in conditioned space.

2. **Report for Code Officials on Variance for Unvented "Cathedralized" Attics.** This provides technical information that builders can present to a code official when requesting a variance to build a house that follows one of the recommended approaches to putting ducts in conditioned space.

The Buildings Program Area within the Public Interest Energy Research (PIER) Program produced these documents as part of a multi-project programmatic contract (#400-99-413). The Buildings Program includes new and existing buildings in both the residential and the non-residential sectors. The program seeks to decrease building energy use through research that will develop or improve energy efficient technologies, strategies, tools, and building performance evaluation methods.

For other reports produced within this contract or to obtain more information on the PIER Program, please visit www.energy.ca.gov/pier/buildings or contact the Commission's Publications Unit at 916-654-5200. All reports, guidelines and attachments are also publicly available at www.newbuildings.org/pier.

ABSTRACT

The “Costs & Savings for Houses Built with Ducts in Conditioned Space: Technical Information Report” is a set of two reports produced as part of the Integrated Design of Residential Ducting & Air Flow Systems project. This was one of six research projects within the *Integrated Energy Systems: Productivity and Building Science* Program, funded by the California Energy Commission’s Public Interest Energy Research (PIER) Program.

Traditionally, California houses have the furnace or air handler and ductwork located in the attic. The resulting air leaks, reduced air flow, and increased infiltration can lead to significant energy losses and comfort problems. This research project identified energy-efficient options for building homes with ducts in conditioned space while maximizing usable floor area, minimizing energy and construction costs, and simplifying the construction process. This attachment consists of two reports:

- **Costs and Energy Savings for Homes with Ducts in Conditioned Space: Technical Information Package.** Contains estimates of construction cost impacts and energy savings for houses built in California with ducts in conditioned space. The researchers found that building houses with ducts in conditioned space is technically feasible and can be done at fairly small cost increments. The cost impact to the builder is 0% to 3% of construction costs. Significant energy savings and energy-cost savings can be achieved.
- **Report for Code Officials on Variance for Unvented “Cathedralized” Attics.** This provides technical information to assist code officials when a builder requests a variance on a home design that used an unvented cathedralized attic approach to putting ducts in conditioned space.

Author: Roger Hedrick, GARD Analytics, Inc.

Key words: home building, duct, conditioned space, unconditioned space, air handler, air leak, infiltration, energy efficient home, residential building code, energy code

Costs and Energy Savings for Homes with Ducts in Conditioned Space

Technical Information Package

Deliverable 6.4.2-e

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Integrated Energy Systems
Productivity and Building Science

On behalf of the:
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Public Interest Energy Research (PIER) Program

October 1, 2003

Integrated Design of Residential Ducting and Airflow Systems
Roger Hedrick

GARD Analytics
Energy, Economic and Environmental Research

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This report is a part of the *Integrated Energy Systems — Productivity and Building Science* project, a Public Interest Energy Research (PIER) program. It is funded by California ratepayers through California's System Benefit Charges administered by the California Energy Commission under (PIER) contract No. 400-99-013, and managed by the New Buildings Institute.

Project Director: Roger Hedrick, GARD Analytics, Inc.

Technical Assistance: Geof Syphers, XENERGY; Rob Hammon, ConSol; Bill Irvine, BCI Testing.

Review and Advisory Committee: Rick Chitwood, Chitwood Energy Management; Iain Walker, Lawrence Berkeley National Laboratory; Joe Lstiburek, Building Science Corporation; Bruce Wilcox, Berkeley Solar Group; Jamie Lyons, Energetics, Inc; Marshall Hunt, Pacific Gas and Electric.

Project Management: Cathy Higgins, Program Director for the New Buildings Institute and Don Aumann, Contract Manager for the California Energy Commission.

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ABOUT PIER

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission, annually awards up to $62 million to conduct the most promising public interest energy research by partnering with research, development and demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

1. Buildings End-use Energy Efficiency
2. Industrial/Agricultural/Water End-use Energy Efficiency
3. Renewable Energy
4. Environmentally Preferred Advanced Generation
5. Energy-Related Environmental Research
6. Strategic Energy Research.

This project contributes to #1 above, the PIER Buildings Program Area. For more information on the PIER Program, please visit the Commission's Web site at: www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200. For other public reports within the *Integrated Energy Systems — Productivity and Building Science* project, please visit www.newbuildings.org/pier

LEGAL NOTICE

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SUMMARY

This report describes the estimates of construction cost impacts and energy savings for houses built in California with ducts in conditioned space. Cost impacts are estimated using multiple methods and data sources. Energy savings estimates include energy, electrical energy demand and energy cost savings. Both the cost impacts and savings are estimated based on three representative house designs for different house sizes, in different climate zones, and for three different approaches to building ducts in conditioned space. Savings were estimated for two different baseline duct leakage cases: 22% and 6% duct leakage.

Three approaches to moving the ducts into the conditioned space were analyzed. The approaches are: dropped ceiling, cathedralized attic and plenum truss. Cost impacts for the approaches applied to three different houses resulted in construction cost increases that ranged from $0 to $800 for the dropped ceiling approach, $0 to $1,000 for the cathedralized attic approach and $2,000 to $4,000 for the plenum truss approach.

Energy savings for individual houses were highly dependent on house size and style, as well as climate. The approach used had relatively little impact on the energy savings. The fraction of duct leakage that escaped to the outdoors for the tested dropped ceiling houses was about half the amount for the cathedralized attic houses. The leakage for all tested houses, however, was quite low.

The statewide average energy savings are expected to be about 800 kWh/year for the townhouse, 2,000 kWh/year for the single story house, and about 3,400 kWh/year for the two story house. For the most severe climates, the savings will be about 3 times the statewide averages, i.e., 2,300 to 8,200 kWh/year. These energy savings translate into cost savings ranging from $189 to $1,285 per year.

The cumulative statewide electricity savings are estimated to be 692,000 MWh at the end of 10 years, based on penetration rates which increase to 10% of new houses being built with ducts in conditioned space after 10 years.

BACKGROUND

Other researchers' reports have described techniques used to build houses with ducts in conditioned space and focused on changes to standard practice for designers, builders, and the various subcontractors[1] (listed in the). Other reports under this element of the PIER program described market barriers and strategies to overcome them, and cost estimates for building ducts in conditioned space. A final guideline document[2] will combine the information from these four reports that is relevant to the builder/contractor audience into a single package, as well as documents aimed at local code officials and

[1] For references of related research see the "Literature Search" report, product 6.3.1 in Attachment A-29 to the PIER Final Report (document # 500-03-082) at www.energy.ca.gov/pier/buildings

[2] Home Builders Guide to Ducts in Conditioned Space, product 6.3.4 - Attachment A16. See web site location for access in footnote 1 above.

consumers. These documents are available at http://www.newbuildings.org by following the "PIER" link or at http://www.energy.ca.gov/pier/buildings.

INTRODUCTION

New houses in California typically are built with the air handler and ductwork located in the unconditioned attic.The ductwork is commonly built with ductboard plenums and flex duct, insulated to R4.2, or sometimes R6 (code requirement is R4.2). In recent years, numerous studies have found large energy losses from these systems, primarily due to air leaks in the air handler and duct system, but also including heat conducted through the duct material. These losses are especially deleterious in the summer when solar radiation can elevate the attic temperature well above the outdoor air temperature. Previous studies have found that typical duct systems can lose over 30% of the space conditioning energy consumed by the HVAC system.

Air leaks on the supply side of the system are lost to the unconditioned attic and eventually to the outdoors, while leaks on the return side result in unconditioned air being brought into the system, increasing the space conditioning load. Unbalanced leakage (for example, large return leaks with small supply leaks) can significantly affect the air pressure in the house resulting in increased infiltration and the corresponding increase in space conditioning loads. Leakage can also cause comfort problems by reducing supply air flow to the house or to individual rooms, and by increasing infiltration.

The problem of duct leakage has primarily been addressed through a variety of programs aimed at reducing leakage in the duct system. These include several utility company programs that provided training to duct installers followed by duct leakage testing. The Title 24 ACM manual now includes a credit for ducts with tested leakage below 6% of system airflow. These programs have reduced typical duct leakage in new construction, but many builders do not take advantage of the Title 24 energy credit. It is estimated that only 30% of homes are built with low leakage ducts (6% of supply airflow) and that the remainder are built with typical duct leakage values of around 20% to 25% of system airflow. And, ducts are still located in the unconditioned attic where the leaks and thermal conduction is lost to the outdoors.

OVERVIEW

Placing ducts in conditioned space involves modifying the design and construction of the house such that the duct system is located inside both the air barrier and the thermal barrier. Different approaches are used to make this change, and each has advantages and disadvantages. Each approach, however, is used to find the best compromise between maximizing marketable floor area, minimizing energy cost, and minimizing construction cost impacts, while keeping the construction process as simple as possible.

In order to optimize the house design choices, information on the construction cost impacts of building homes with ducts in the conditioned space must be provided, as well as estimates of the energy savings that can be expected. We have addressed these needs by working with some California production builders to obtain cost estimates, as well as by getting some cost data from builders and researchers who have built homes, either production or prototype, with ducts in conditioned space. Energy savings were estimated based on data collected from testing of a number of houses built in California with ducts in conditioned space. The test results were described in a previous report, *Tests of Homes with Ducts in Conditioned Space*. This report utilizes that data and describes the analyses performed to provide generalized estimates for energy savings.

This report briefly describes the necessary changes from conventional construction for each of three approaches to building houses with ducts in conditioned space, and provides estimates of the cost of each change. Three house designs, a single story, a two-story and a townhouse, are used to illustrate the specifics of the construction changes needed. Costs for changes to these houses were developed using standard cost estimating guides and costs determined from interviews with material suppliers. Three builders also developed cost estimates, based on designs of their own which are currently being built with conventional HVAC systems. Cost estimates from builders currently building homes with ducts in conditioned space and from a researcher who developed one approach are also discussed.

The same three houses were used to estimate energy savings. Simulations using DOE-2 were run for each house in 12 California climate zones. House characteristics such as insulation levels and glazing properties were adjusted by climate zone according to Title 24 requirements.

THREE APPROACHES

Three approaches to building ducts in conditioned space have been developed and applied to actual houses. These three are: Dropped Ceiling, Cathedralized Attic, and Plenum Truss.

The **Dropped Ceiling** approach is applied to houses with high ceilings, 9' to 10'. In hallways and other ancillary spaces, a dropped ceiling is installed at 8' high, with the ducts installed in the space between. By providing an air barrier at the 9' or 10' ceiling height, the duct space is brought into conditioned space. Supply registers are located on interior walls, adjacent to the dropped ceiling.

The **Cathedralized Attic** approach is applied to houses with conventional pitched attics. The roof deck is air sealed to provide the primary air barrier, i.e., ridge and soffit vents are not used. The ceiling insulation is moved to the roof level, and installed immediately below the roof deck. With the air and thermal barriers moved to the roof, the attic is brought into conditioned space. The HVAC system is then installed in the attic as it normally is. The houses that have been built with this approach have generally used interior register locations.

The **Plenum Truss** approach is also applied to houses with conventional attics. A modified scissors truss is used to provide a space between the ceiling and the bottom chord of the trusses. Sheet material, such as fiberboard, is installed on the bottom chord of the trusses, and sealed to provide the air barrier. Insulation is then installed above. The space between the bottom chord of the trusses and the ceiling is then inside conditioned space, and used for HVAC system installation. The conditioned duct space may not extend to the full width of the attic, so again interior supply register locations are used.

For **all three approaches**, interior register locations have been used for most houses. In the past, being near exterior walls was less comfortable than elsewhere in the house. This was due to poor wall insulation and windows with poor U-values allowing the wall surface temperatures to be cold (or hot). This caused the radiant temperature to be lower (or higher) than the desired space temperature, as well as drafts caused by convective heat transfer. Additionally, windows were sometimes leaky, allowing additional drafts. Locating supply registers near exterior walls allowed the supply air to wash over the exterior wall, bringing the surface temperature closer to the space temperature, and breaking up drafts. Current California housing, however, has better insulation, lower air leakage, and better windows. Together, these improvements minimize the discomfort effects described above. As a result, the need for exterior supply registers disappears. This allows the use of interior register locations, which provide benefits to the builder through reduced duct material (the duct runs are shorter), and energy benefits because there is less duct surface area, minimizing thermal conduction. With the interior register locations, however, it is desirable to use higher quality registers that will provide better mixing in the space.

CONSTRUCTION CHANGES

The *Home Builders Guide to Ducts in Conditioned Space* describes the changes from conventional construction techniques required to build houses with ducts in conditioned space. The cost of the changes will vary with the characteristics of the house, the climate and design choices made.

Dropped Ceiling

Use of the dropped ceiling approach has four main changes to conventional construction which affect costs:

- Add framing to the bottom of the dropped ceiling area
- Install an air barrier at top of dropped ceiling
- Seal the air barrier
- Install compact duct system (Note: a compact duct system uses supply registers located on or near to interior walls, resulting in shorter duct runs.)

Cathedralized Attic

The major changes for the cathedralized attic approach are:

- Delete roof venting devices
- Install netting for insulation between trusses
- Install roof insulation between trusses (increased insulation area)
- Seal openings around roof edges
- Optionally install compact duct system (ductwork reductions)
- Do not install insulation between the top floor ceiling joists

Plenum Truss

The major changes for the plenum truss approach are:

- Install revised design trusses
- Add framing to the floor of plenum
- Install an air barrier on underside of trusses
- Seal the air barrier
- Optionally install compact duct system (ductwork reductions)

HOUSE TYPES

The three approaches were applied to three housing types, a one story house, a two story house and a townhouse. The best approach for a given house type is determined by the climate zone, the duct air leakage and the construction details of the house.

One Story Houses

All three approaches can be applied and are cost effective on single story houses. The approach most appropriate will depend upon the design of the house and the climate zone that the house is located in. The selection of the approach is extremely critical when low leakage duct systems are used. For low leakage duct systems, cathedralized attics are only cost effective in some locations and the plenum truss is typically not cost effective.

Two Story Houses

Bringing ducts inside conditioned space for a two story house requires application of one of the above approaches to the top floor, with ducts serving the lower floor installed between the two floors. The area between floors must be sealed to maintain a continuous air barrier between the first and second floors. This is accomplished by sealing top and bottom of band joist, and the vertical penetrations at the roof air barrier.

All three approaches are cost effective on two story houses but the plenum truss approach is only cost effective in some climate zones when used with low leakage duct construction.

Town Houses

All three approaches can be used on town houses but only the dropped ceiling approach is cost effective with low leakage duct construction. As with the other housing type, the most appropriate approach will depend upon the design of the house and the climate zone that the house is located in.

General

For all three approaches, there will be a reduction in peak loads on the space heating equipment, which will often allow a reduction in capacity of the heating and cooling units.

CONSTRUCTION COSTS

Construction costs estimates are based on the impact to the builder and were developed in three ways.

1. Costing using standard cost estimating guides and component costs determined from interviews with subcontractors and material suppliers. These costs are based on three houses, previously described in Deliverable 6.3.3, Representative House Designs Summary Report.
2. Cost estimates prepared by production builders. Three production home builders estimated cost impacts of modifying two of their designs currently in production to build them with ducts in conditioned space.
3. Cost estimates from a builder currently using the cathedralized attic approach and from the researcher who developed the plenum truss approach.

In all three cases, the costs are costs to the builder. Costs to the home buyer will be marked up by the builder, increasing the final cost by an additional 20% to 30%.

Component Based Costs

In developing the costs using standard cost estimating guides, the specifics of changes required for three particular house designs were identified. The three houses were selected from the nine houses described in Deliverable 6.3.3. The three houses were designs 2, 5 and 8. These houses are a 1,746 ft^2 single story house, a 3,148 ft^2 two story house, and a 1,216 ft^2 two story townhouse.

The tables below show the cost change estimates for each house design using each approach. For the cathedralized attic approach, two versions are shown, depending on the level of roof insulation required, R-30 or R-38. For the cathedralized attic and plenum truss approaches, the costs are also shown with no changes to the duct system and with using a compact duct system. Theoretically, the choice of standard or compact duct systems for these approaches is separate from the decision to build with ducts in conditioned space. The homes built to date, however, have all used compact duct systems. For this reason, costs will be shown both ways.

Deliverable 6.3.4b describes how in cooler climates (i.e., lowest monthly average temperature below 45 F), houses built with cathedralized attics will need to have insulation installed above the roof deck in order to avoid moisture problems. The cost of such insulation is not included in the estimates below.

Table 1 - Dropped Ceiling Costs for One Story Single Family (Design 2)

	Materials					Labor					
	unit	# units	$/unit	Markup	Subtotal	Unit	# units	$/unit	Markup	Subtotal	**TOTAL**
Dropped Ceiling											
Framing bottom of dropped ceiling	ft²	400	0.36	0.25	180.00	ft²	400	0.48	1.70	517.63	**697.63**
Sheets of air barrier - OSB, plywood, etc.	ea	13	4.50	0.25	73.13	ft²	416	0.22	1.70	246.74	**319.86**
200 linear feet of sealing	ft²	400	0.50	0.25	250.00	Ft	200	0.06	1.70	32.95	**282.95**
Compact duct system											
5" - 30 ft. to 20 ft.	ft.	-10	0.986	0.25	-12.33	ft.	-10	1.170	1.68	-31.40	-43.73
6" - 2 ft. (no change)	ft.	0	1.134	0.25	0.00	ft.	0	1.350	1.68	0.00	0.00
7" - 26 ft. to 17 ft.	ft.	-9	1.049	0.25	-11.80	ft.	-9	1.600	1.68	-38.65	-50.45
8" - 72 ft. to 48 ft.	ft.	-24	1.348	0.25	-40.43	ft.	-24	1.950	1.68	-125.61	-166.04
9" - 36 ft. to 24 ft.	ft.	-12	1.500	0.25	-22.50	ft.	-12	2.300	1.68	-74.08	-96.58
10" - 38 ft. to 25 ft.	ft.	-13	1.645	0.25	-26.73	ft.	-13	2.700	1.68	-94.21	-120.94
12" - 17 ft. to 12 ft.	ft.	-5	2.032	0.25	-12.70	ft.	-5	3.510	1.68	-47.10	-59.80
Subtotal					**-126.49**					**-411.05**	**-537.54**
Dropped Ceiling Total					**376.64**					**386.27**	**762.91**

Table 2 - Cathedralized Attic Costs for One Story Single Family (Design 2)

	Materials					Labor					
	unit	# units	$/unit	Markup	Subtotal	unit	# units	$/unit	Markup	Subtotal	**TOTAL**
Delete Roof Venting											
Gable end vents	in²	-621	0.29	0.25	-223.17	in²	-621	0.24	1.70	-401.81	**-624.98**
High dormer vent	in²	-100	0.29	0.25	-35.94	in²	-100	0.24	1.70	-64.70	**-100.64**
Eave vents	in²	-531	0.29	0.25	-190.83	in²	-531	0.24	1.70	-343.58	**-534.41**
Insulation netting between trusses											
2100 ft²	ft²	2100	0.19	0.25	498.75	ft²	2100	0.22	1.70	1245.55	**1744.30**
Insulation - increase area from 2155 ft² to 2263 ft²											
R-30	ft²	108	3.65	0.25	492.75	ft²	108	0.25	1.70	72.79	**565.54**
R-38	ft²	108	4.30	0.25	580.50	ft²	108	0.30	1.70	87.35	**667.85**
Sealing around roof perimeter											
200 linear feet	ft.	200	0.60	0.25	150.00	ft	200	0.06	1.70	32.95	**182.95**
Compact duct system											
5" - 30 ft. to 20 ft.	ft.	-10	0.986	0.25	-12.33	ft.	-10	1.170	1.68	-31.40	-43.73
6" - 2 ft. (no change)	ft.	0	1.134	0.25	0.00	ft.	0	1.350	1.68	0.00	0.00
7" - 26 ft. to 17 ft.	ft.	-9	1.049	0.25	-11.80	ft.	-9	1.600	1.68	-38.65	-50.45
8" - 72 ft. to 48 ft.	ft.	-24	1.348	0.25	-40.43	ft.	-24	1.950	1.68	-125.61	-166.04
9" - 36 ft. to 24 ft.	ft.	-12	1.500	0.25	-22.50	ft.	-12	2.300	1.68	-74.08	-96.58
10" - 38 ft. to 25 ft.	ft.	-13	1.645	0.25	-26.73	ft.	-13	2.700	1.68	-94.21	-120.94
12" - 17 ft. to 12 ft.	ft.	-5	2.032	0.25	-12.70	ft.	-5	3.510	1.68	-47.10	-59.80
Subtotal					**-126.49**					**-411.05**	**-537.54**
Cathedralized Attic Totals											
Standard Ducts, R30					**691.56**					**541.20**	**1232.76**
Compact Ducts, R30					**565.08**					**130.15**	**695.22**
Standard Ducts, R38					**779.31**					**555.76**	**1335.07**
Compact Ducts, R38					**652.83**					**144.70**	**797.53**

Table 3 - Plenum Truss Costs for One Story Single Family (Design 2)

	Materials					Labor					
	unit	# units	$/unit	Markup	Subtotal	unit	# units	$/unit	Markup	Subtotal	**TOTAL**
Revised Trusses											
1746 ft²	ft²	1746	0.00	0.00	0.00	ft²	1746	0.0	1.70	0.00	**0.00**
Framing floor of Plenum - 55 ft long											
20 ft span	ft²	1100	0.57	0.00	627.00	ft²	1100	0.48	1.70	1423.49	**2050.49**
Air Barrier on underside of trusses											
38 sheets of 1/8" laminated fiber sheathing (Thermoply, FiberLam)	ea.	38	5.60	0.25	266.00	ft²	1216	0.30	1.70	983.50	**1249.50**
600 linear feet of sealing	ft²	1216	0.50	0.25	760.00	ft	200	0.06	1.70	32.95	**792.95**
Air Barrier at garage (installed vertically)											
5 sheets of thermoply	ea.	5	5.60	0.25	35.00	ft²	160	0.30	1.70	129.41	**164.41**
85 ft of sealing	ft²	160	0.50	0.25	100.00	ft	85	0.06	1.70	14.00	**114.00**
Compact duct system											
5" - 30 ft. to 20 ft.	ft.	-10	0.986	0.25	-12.33	ft.	-10	1.170	1.68	-31.40	-43.73
6" - 2 ft. (no change)	ft.	0	1.134	0.25	0.00	ft.	0	1.350	1.68	0.00	0.00
7" - 26 ft. to 17 ft.	ft.	-9	1.049	0.25	-11.80	ft.	-9	1.600	1.68	-38.65	-50.45
8" - 72 ft. to 48 ft.	ft.	-24	1.348	0.25	-40.43	ft.	-24	1.950	1.68	-125.61	-166.04
9" - 36 ft. to 24 ft.	ft.	-12	1.500	0.25	-22.50	ft.	-12	2.300	1.68	-74.08	-96.58
10" - 38 ft. to 25 ft.	ft.	-13	1.645	0.25	-26.73	ft.	-13	2.700	1.68	-94.21	-120.94
12" - 17 ft. to 12 ft.	ft.	-5	2.032	0.25	-12.70	ft.	-5	3.510	1.68	-47.10	-59.80
Subtotal					**-126.49**					**-411.05**	**-537.54**
Plenum Truss Totals											
Standard Ducts					**1788.00**					**2583.35**	**4371.35**
Compact Ducts					**1661.51**					**2172.30**	**3833.81**

Table 4 - Dropped Ceiling Costs for Two Story Single Family (Design 5)

	Materials					Labor					
	unit	# units	$/unit	Markup	Subtotal	Unit	# units	$/unit	Markup	Subtotal	TOTAL
Between floor volume											
Seal band joist, top and bottom of joist	ft.	200	0.60	0.25	150.00	Ft	400	0.06	1.70	65.90	215.90
Dropped Ceiling											
framing bottom of dropped ceiling	ft²	405	0.36	0.25	182.25	ft²	405	0.48	1.70	524.10	706.35
Sheets of air barrier - OSB, plywood, etc.	ea.	13	4.50	0.25	73.13	ft²	416	0.22	1.70	246.74	319.86
200 linear feet of sealing	ft²	405	0.50	0.25	253.13	ft	200	0.06	1.70	32.95	286.08
Compact duct system											
4" - 41 ft. to 21 ft.	ft.	-20	0.866	0.25	-21.66	ft.	-20	1.030	1.68	-55.29	-76.95
6" - 26 ft. to 13 ft.	ft.	-13	1.134	0.25	-18.42	ft.	-13	1.350	1.68	-47.10	-65.53
7" - 86 ft. to 43 ft.	ft.	-43	1.049	0.25	-56.37	ft.	-43	1.600	1.68	-184.66	-241.03
8" - 122 ft. to 40 ft.		-82	1.348	0.25	-138.13	ft.	-82	1.950	1.68	-429.17	-567.30
9" - 55 ft. to 23 ft.	ft.	-32	1.500	0.25	-60.00	ft.	-32	2.300	1.68	-197.54	-257.54
10" - 30 ft. to 15 ft.	ft.	-15	1.645	0.25	-30.85	ft.	-15	2.700	1.68	-108.70	-139.55
12" - 73 ft. to 37 ft.	ft.	-36	2.032	0.25	-91.43	ft.	-36	3.510	1.68	-339.15	-430.58
14" - 33 ft. to 17 ft.	ft.	-16	2.500	0.25	-50.00	ft.	-16	4.320	1.68	-185.52	-235.52
Subtotal					**-466.86**					**-1547.14**	**-2014.00**
Dropped Ceiling Total					**191.64**					**-677.44**	**-485.81**

Table 5 - Cathedralized Attic Costs for Two Story Single Family (Design 5)

	Materials					Labor					
	unit	# units	$/unit	Markup	Subtotal	Unit	# units	$/unit	Markup	Subtotal	**TOTAL**
Between floor volume											
Seal band joist, top and bottom of joist	ft.	200	0.60	0.25	150.00	Ft	400	0.06	1.70	65.90	215.90
Delete Roof Venting											
Gable end vents – High	in²	-288	0.29	0.25	-103.50	In²	-288	0.24	1.70	-186.35	-289.85
Gable end vents – Low	in²	-288	0.29	0.25	-103.50	In²	-288	0.24	1.70	-186.35	-289.85
Overhanging roof vents – High	in²	-285	0.29	0.25	-102.42	In²	-285	0.24	1.70	-184.41	-286.83
Overhanging roof vents – Low	in²	-285	0.29	0.25	-102.42	In²	-285	0.24	1.70	-184.41	-286.83
Overhanging roof vents	in²	-190	0.29	0.25	-68.28	In²	-190	0.24	1.70	-122.94	-191.22
Insulation netting between trusses											
2000 ft²	ft²	2000	0.19	0.25	475.00	ft²	2000	0.22	1.70	1186.24	1661.24
Insulation - increase area from 2000 ft² to 2100 ft²											
R-30	ft²	100	3.65	0.25	456.25	ft²	100	0.25	1.70	67.40	523.65
R-38	ft²	100	4.30	0.25	537.50	ft²	100	0.30	1.70	80.88	618.38
Sealing around roof perimeter											
200 linear feet	ft.	200	0.60	0.25	150.00	ft	200	0.06	1.70	32.95	182.95
Compact duct system											
4" - 41 ft. to 21 ft.	ft.	-20	0.866	0.25	-21.66	ft.	-20	1.030	1.68	-55.29	-76.95
6" - 26 ft. to 13 ft.	ft.	-13	1.134	0.25	-18.42	ft.	-13	1.350	1.68	-47.10	-65.53
7" - 86 ft. to 43 ft.	ft.	-43	1.049	0.25	-56.37	ft.	-43	1.600	1.68	-184.66	-241.03
8" - 122 ft. to 40 ft.		-82	1.348	0.25	-138.13	ft.	-82	1.950	1.68	-429.17	-567.30
9" - 55 ft. to 23 ft.	ft.	-32	1.500	0.25	-60.00	ft.	-32	2.300	1.68	-197.54	-257.54
10" - 30 ft. to 15 ft.	ft.	-15	1.645	0.25	-30.85	ft.	-15	2.700	1.68	-108.70	-139.55
12" - 73 ft. to 37 ft.	ft.	-36	2.032	0.25	-91.43	ft.	-36	3.510	1.68	-339.15	-430.58
14" - 33 ft. to 17 ft.	ft.	-16	2.500	0.25	-50.00	ft.	-16	4.320	1.68	-185.52	-235.52
Subtotal					**-466.86**					**-1547.14**	**-2014.00**
Cathedralized Attic Totals											
Standard Ducts, R30					**751.13**					**488.05**	**1239.17**
Compact Ducts, R30					**284.26**					**-1059.09**	**-774.83**
Standard Ducts, R38					**832.38**					**501.53**	**1333.90**
Compact Ducts, R38					**365.51**					**-1045.61**	**-680.10**

Table 6 - Plenum Truss Costs for Two Story Single Family (Design 5)

	Materials					Labor					
	unit	# units	$/unit	Markup	Subtotal	unit	# units	$/unit	Markup	Subtotal	**TOTAL**
Between floor volume											
Seal band joist, top and bottom of joist	ft.	200	0.60	0.25	150.00	ft	400	0.06	1.70	65.90	**215.90**
Revised Trusses											
2000 ft²	ft²	2000	0.00	0.00	0.00	ft²	2000	0.0	1.70	0.00	**0.00**
Framing floor of Plenum – 60 ft long											
25 ft span	ft²	1100	0.88	0.25	1210.00	ft²	1100	0.55	1.70	1631.08	**2841.08**
Air Barrier on underside of trusses											
50 sheets of 1/8" laminated fiber sheathing (Thermoply, FiberLam)	ea.	50	5.60	0.25	350.00	ft²	1600	0.30	1.70	1294.08	**1644.08**
800 linear feet of sealing	ft²	1600	0.50	0.25	1000.00	ft	800	0.06	1.70	131.80	**1131.80**
Compact duct system											
4" - 41 ft. to 21 ft.	ft.	-20	0.866	0.25	-21.66	ft.	-20	1.030	1.68	-55.29	-76.95
6" - 26 ft. to 13 ft.	ft.	-13	1.134	0.25	-18.42	ft.	-13	1.350	1.68	-47.10	-65.53
7" - 86 ft. to 43 ft.	ft.	-43	1.049	0.25	-56.37	ft.	-43	1.600	1.68	-184.66	-241.03
8" - 122 ft. to 40 ft.		-82	1.348	0.25	-138.13	ft.	-82	1.950	1.68	-429.17	-567.30
9" - 55 ft. to 23 ft.	ft.	-32	1.500	0.25	-60.00	ft.	-32	2.300	1.68	-197.54	-257.54
10" - 30 ft. to 15 ft.	ft.	-15	1.645	0.25	-30.85	ft.	-15	2.700	1.68	-108.70	-139.55
12" - 73 ft. to 37 ft.	ft.	-36	2.032	0.25	-91.43	ft.	-36	3.510	1.68	-339.15	-430.58
14" - 33 ft. to 17 ft.	ft.	-16	2.500	0.25	-50.00	ft.	-16	4.320	1.68	-185.52	-235.52
Subtotal					**-466.86**					**-1547.14**	**-2014.00**
Plenum Truss Totals											
Standard Ducts					**2710.00**					**3122.87**	**5832.87**
Compact Ducts					**2243.14**					**1575.73**	**3818.87**

Table 7 - Dropped Ceiling Costs for Townhouse (Design 8)

	Materials					Labor					
	unit	# units	$/unit	Markup	Subtotal	unit	# units	$/unit	Markup	Subtotal	**TOTAL**
Between floor volume											
Seal band joist, top and bottom of joist	ft.	108	0.60	0.25	81.00	ft	216	0.06	1.70	35.59	**116.59**
Dropped Ceiling											
framing bottom of dropped ceiling	ft²	68	0.36	0.25	30.60	ft²	68	0.48	1.70	88.00	**118.60**
Sheets of air barrier - OSB, plywood, etc.	ea.	3	4.50	0.25	16.88	ft²	96	0.22	1.70	56.94	**73.81**
50 linear feet of sealing	ft²	68	0.50	0.25	42.50	ft	50	0.06	1.70	8.24	**50.74**
Dropped Ceiling Total					**170.98**					**188.76**	**359.74**

Table 8 - Cathedralized Attic Costs for Townhouse (Design 8)

	Materials					Labor					
	unit	# units	$/unit	Markup	Subtotal	unit	# units	$/unit	Markup	Subtotal	**TOTAL**
Between floor volume											
Seal band joist, top and bottom of joist	ft.	108	0.60	0.25	81.00	ft	216	0.06	1.70	35.59	**116.59**
Delete Roof Venting											
8" by 18" metal louver attic vent	ea	144	0.29	0.25	51.75	in²	144	0.24	1.70	93.17	**144.92**
Insulation netting between trusses											
720 ft²	ft²	720	0.19	0.25	171.00	ft²	720	0.22	1.70	427.05	**598.05**
Insulation - increase area from 2155 ft² to 2263 ft²											
R-30	ft²	40	3.65	0.25	182.50	ft²	40	0.25	1.70	26.96	**209.46**
R-38	ft²	40	4.30	0.25	215.00	ft²	40	0.30	1.70	32.35	**247.35**
Sealing around roof perimeter											
108 linear ft.	ft.	108	0.60	0.25	81.00	ft	108	0.06	1.70	17.79	**98.79**
Cathedralized Attic Totals											
Compact Ducts, R30					**567.25**					**600.56**	**1167.81**
Compact Ducts, R38					**599.75**					**605.95**	**1205.70**

Table 9 - Plenum Truss Costs for Townhouse (Design 8)

	Materials					Labor					
	unit	# units	$/unit	Markup	Subtotal	unit	# units	$/unit	Markup	Subtotal	**TOTAL**
Between floor volume											
Seal band joist, top and bottom of joist	ft.	108	0.60	0.25	81.00	ft	216	0.06	1.70	35.59	**116.59**
Revised Trusses											
720 ft²	ft²	720	0.00	0.00	0.00	ft²	720	0.0	1.70	0.00	**0.00**
Framing floor of Plenum - 24 ft long											
20 ft span	ft²	480	0.57	0.25	342.00	ft²	480	0.48	1.70	621.16	**963.16**
Air Barrier on underside of trusses											
24 sheets of 1/8" laminated fiber sheathing (Thermoply, FiberLam)	ea.	24	5.60	0.25	168.00	ft²	768	0.30	1.70	621.16	**789.16**
300 linear feet of sealing	ft²	768	0.50	0.25	480.00	ft	300	0.06	1.70	49.43	**529.43**
Plenum Truss Totals											
Compact Ducts					**1071.00**					**1327.33**	**2398.33**

Table 10 - Cost Premium Summary

	One Story Single Family		Two Story Single Family		2 Story Townhouse
	Std. Ducts	Compact Ducts	Std. Ducts	Compact Ducts	Compact Ducts
Dropped Ceiling Total	N/A	762.91	N/A	-485.81	188.76
Cathedralized Attic Total - R30	1232.76	695.22	1239.17	-774.83	1167.81
Cathedralized Attic Total - R38	1335.07	797.53	1333.90	-680.10	1205.70
Plenum Truss Total	4371.35	3833.81	5832.87	3818.87	2398.33

From the Cost Summary table above, the effects of house configuration on the relative cost of the different approaches is apparent. For the two single family houses, the dropped ceiling and cathedralized attic with compact duct system approaches had very similar costs. For the townhouse, on the other hand, the dropped ceiling approach is significantly less expensive. This is primarily due to the compact floor plan of this design, with a relatively small dropped ceiling area. Also, this design used a compact duct system already, so the cost savings for this aspect of the cathedralized attic approach are not available. For all three houses, the plenum truss approach is significantly more expensive, although the cost premium is lower as the house floor area is less.

None of the costs shown above include savings due to reduction in the capacity of the central heating and cooling equipment. As the central equipment is downsized, reduced airflow may allow the duct diameters to be reduced as well. The table below shows the costs of various sizes of central heating and cooling equipment, along with the savings available by moving from one size to the next smaller size. The effect of any related changes to the duct system are not included. It is apparent, however, that load reductions sufficient to allow the next smaller system size to be used offers substantial savings in first costs.

In many cases, the overall cost impact of building houses with ducts in conditioned space, particularly when smaller capacity central equipment can be used, is negative, i.e., a net cost savings.

Table 11 - Cost of Central Gas Furnace/Electric Air Conditioner Equipment

Capacity	Equipment	Installation Labor	Total Cost	Difference vs. Next Size Up
6 ton	6600.00	5368.00	11968.00	-
5 ton	6270.00	3556.30	9826.30	**-2141.70**
4 ton	6000.00	2053.26	8053.26	**-1773.04**
3.5 ton	5000.00	1905.64	6905.64	**-1147.62**
3 ton	4200.00	1583.56	5783.56	**-1122.08**
2.5 ton	3700.00	1342.00	5042.00	**-741.56**
2 ton	3300.00	1207.80	4507.80	**-534.20**

Production Builder Estimates

Three California production builders provided costs estimates for the various approaches to constructing houses with ducts in conditioned space. In each case, they identified two existing house models, currently in production. The specific changes needed to implement ducts in conditioned space were identified from Deliverable 6.3.4a, *Alternative Design Details for Building Houses with Ducts in Conditioned Space*. Characteristics of the six houses identified for evaluation are summarized in the table below.

Table 12 - Production Houses Used for Costing

House ID	Description	Floor Area	Climate Zone
1	Two Story, Single Family Detached	2493	12
2	Two Story, Single Family Detached	2057	12
3	Three Story Townhouse	1755	4
4	Two Story, Single Family Detached	1931	4
5	Two Story, Single Family Detached	1954	10
6	One Story, Single Family Detached	1287	10

Each builder provided a spreadsheet with cost breakouts for the approaches evaluated. Not all the builders provided costs for all three approaches. The cost breakdowns from the builders are provided below.

Table 13 - Cost Impacts for House 1

Item	Dropped Ceiling	Plenum Truss	Cathedralized Attic
Build Garage soffit	$100	$100	$100
Insulate both soffits in garage (existing and new)	$100	$100	$100
Drywall upstairs lid in new soffit area	$300	$300	$300
Cost for special trusses	$0	$400	$0
Framing	incl	$300	incl
Blocking / Sheet Material	incl	$150	$150
Build upstairs soffit – Labor	$900	incl	incl
Build upstairs soffit – Material	$400	incl	incl
Banjoist / Rim Sealing / Insulation	$136	$136	$136
Total	**$1,936**	**$1,486**	**$786**

Table 14 - Cost Impacts for House 2

Item	Dropped Ceiling	Plenum Truss	Cathedralized Attic
Build Garage soffit	$100	$100	$100
Insulate both soffits in garage (existing and new)	$100	$100	100
Drywall upstairs lid in new soffit area	$300	$300	$300
Cost for special trusses	$0	$400	$0
Framing	incl	$300	Incl
Blocking / Sheet Material	incl	$150	$150
Build upstairs soffit – Labor	$900	incl	Incl
Build upstairs soffit – Material	$400	incl	Incl
Banjoist / Rim Sealing / Insulation	$123	$123	$123
Total	**$1,923**	**$1,473**	**$773**

Table 15 - Cost Impacts for House 3

Item	Dropped Ceiling
Extra Foam Sealant	$120
Build soffit – Labor	$845
Build soffit – Material	$243
Banjoist / Rim Sealing/Insulation	$104
Drywall	$1,654
Total	**$2,966**

Table 16 - Cost Impacts for House 4

Item	Dropped Ceiling
Extra Foam Sealant	$120
Build soffit – Labor	$845
Build soffit – Material	$268
Banjoist / Rim Sealing/Insulation	$125
Drywall	$1,654
Total	**$3,012**

Table 17 - Cost Impacts for House 5

Item	Dropped Ceiling	Cathedralized Attic
Framing and Labor	$580	
Lighting / Penetration	$150	
Sealant	$100	
Drywall	$500	
Banjoist / Rim Sealing/Insulation	$101	
Total	**$1,431**	**$1,073**

Table 18 - Cost Impacts for House 6

Item	Dropped Ceiling	Cathedralized Attic
Framing and Labor	$500	
Lighting / Penetration	$150	
Drywall	$500	
Sealant	$100	
Total	**$1,250**	**$938**

Table 19 - Summary of Builder Cost Estimates

ID	Climate Zone	Dropped Ceiling	Cathedralized Attic	Plenum Truss
House 1	12	$1,936	$786	$1,486
House 2	12	$1,923	$773	$1,473
House 3	4	$2,966		
House 4	4	$3,012		
House 5	10	$1,431	$1,073	
House 6	10	$1,250	$938	

The cost estimates from the production builders tell a different story from the component based cost estimates. Unfortunately, the level of detail is insufficient to gain much insight. Costs are positive in all cases, i.e., building ducts in conditioned space is expected to increase costs in all cases. The single builder who provided an estimate for the plenum truss approach estimated that it would cost less than the dropped ceiling approach, even though he included a cost increase for the trusses themselves (estimated to have no cost impact in the component based estimates). In all cases, the dropped ceiling approach was expected to be the most expensive of the three options. Also, none of the builders included any savings for a compact duct system. Finally, based on the builder cost estimates, the size of the house does not have much effect on the cost. The houses used by the builders in climate zones 12 and 4 had only small difference in floor area, but the houses used by the builder in climate zone 10 had a large difference in floor area. House 6 has only 66% of the floor area of House 5, but the cost is 87% of the cost for House 6.

Builder and Researcher Estimates

In addition to the cost estimates developed for this project, costs were obtained from a builder in southern California who has houses in production using the cathedralized attic approach. These houses are one story, single family detached houses with floor areas in the 1600 to 2200 ft^2 range. He estimates that building the houses with the ducts in conditioned space increases costs by \$0.70 /ft^2, or \$1,120 to \$1,540. This cost, however, also includes the cost of an outdoor air duct to the return side of the duct system, and jump ducts to provide a return air path from bedrooms when the doors are closed to minimize pressure imbalances. Costs for these ducts are not included in any of the previous cost estimates.

The researcher who has developed the plenum truss approach also provided a cost estimate based on their prototype houses in Florida. Based on the revised scissors trusses requiring the same or fewer board-feet of lumber, there is no cost increase for the trusses themselves, the ceiling and air barrier is estimated to cost \$600, and a 1/2 ton reduction in central HVAC equipment capacity saves \$275, for a total of \$325. It is unclear what size house this estimate applies to, but in any case, this estimate is significantly lower than the previous estimates.

Cost Impact Summary

Three different methods of developing costs for building ducts in conditioned space provided a wide range of values. These are summarized in the following table.

Table 20 - Cost Estimate Summary

Estimating Method	Duct Design	Dropped Ceiling	Cathedralized Attic		Plenum Truss	
			Standard Ducts	Compact Ducts	Standard Ducts	Compact Ducts
Component	Design 2 – R 30	763	1,233	695	4,371	3,834
Component	Design 2 – R-38	763	1,335	798	4,371	3,834
Component	Design 5 – R 30	-486	1,239	-775	5,833	3,819
Component	Design 5 – R-38	-486	1,334	-680	5,833	3,819
Component	Design 8 – R 30	360	—	1,168	—	2,398
Component	Design 8 – R-38	360	—	1,206	—	2,398
Builder Est.	House 1	1,936	786	—	1,486	—
Builder Est.	House 2	1,923	773	—	1,473	—
Builder Est.	House 3	2,966	—	—	—	—
Builder Est.	House 4	3,012	—	—	—	—
Builder Est.	House 5	1,431	1,073	—	—	—
Builder Est.	House 6	1,250	938	—	—	—
Builder	Builder Large	—	—	1,120	—	—
Builder	Builder Small	—	—	1,540	—	—
Researcher	Researcher	—	—	—	325	—

Cost estimates for the cathedralized attic approach are the most consistent, ranging from a savings of nearly $800 to a cost increase of about $1,200, increasing to $1,500 when pressure relief jump ducts and an outdoor air intake are included. Use of a compact duct system offers significant cost savings which are included in these costs. When the savings from the compact duct system are not included, the cost estimates are all between $773 and $1,335, a remarkably tight grouping.

Cost estimates for the dropped ceiling approach vary widely between the estimates from the three production builders and the component based estimates. One source of the difference may be the compact duct system savings included in the component based estimates, but these savings are not large enough to explain all of the difference. It appears that the builders may be assuming that the top of the dropped ceiling will be drywalled. If so, this may also result in significant cost increase, as well as schedule and subcontractor coordination problems. Drywalling the top of the dropped ceiling is not necessary, and the component based approach is based on using low cost plywood with foam sealant.

Cost estimates for the plenum truss approach have the largest spread, from $300 to nearly $6,000. Costs for this approach appear to be closely tied to the size of the house. The variation in the costs appears to be due to variations in the estimated cost for framing the floor of the ceiling plenum, as this is by far the largest cost component for this approach from the component based estimates. The estimates for the floor framing alone exceed the total cost estimates from the production builders and the researcher.

It is difficult to know which of the costs above will be the best predictor of cost impacts for production builders. Costs will likely be higher for the first houses a builder does with ducts in conditioned space, but will drop as experience is gained. Best guess for approximate contractor costs are shown in the table below. Also shown are the costs as a percentage of total construction cost.

These are approximate incremental costs for houses with R-30 roof insulation. The houses also include savings for switching the ducts from a standard design to a compact duct system. If R-39 roof insulation is needed, the cost for the Cathedralized Attic approach will increase by about $100. If the compact duct system savings are not included, i.e., if the baseline house already has a compact duct system, the costs will increase by about $500 for the one story single family and $2,000 for the two story single family. The baseline townhouse design already had a compact duct system, so the cost increase is unknown, but it is likely to be no more than $200 or $300 because of its small size.

Table 21 - Cost Premium Best Estimate (Cost and as Percent of Total Construction Cost)

	Dropped Ceiling		Cathedralized Attic		Plenum Truss	
	$	%	$	%	$	%
One Story Single Family	800	0.5%	700	0.5%	4,000	3%
Two Story Single Family	0	0%	0	0%	4,000	1.5%
Townhouse	400	0.4%	1,000	1%	2,000	2%

ENERGY SAVINGS

Descriptions of the Tested Houses

In order to estimate the energy savings that can be expected from building houses with ducts in conditioned space, a total of 16 houses built in California with ducts in conditioned space were tested. Of these, 12 used the Cathedralized Attic approach, and four used the Dropped Ceiling approach. There were no houses identified which used a Plenum Truss approach. (The only two homes known to have utilized this approach were built in Florida to demonstrate and develop the approach.)

Of the houses with Cathedralized attics, 9 were built by Pulte Homes at their Sun Lakes development in Banning, California. Current construction at this development is made up entirely of three house models, although only two were currently being built and were tested. The other three houses were built by three different builders, and are located in Livermore, El Dorado Hills, and Redding, California.

The four Dropped Ceiling homes were all built with Chitwood Energy Management serving as both the HVAC and the insulation subcontractor. They are all located in North Central California, in Mt. Shasta or Cottonwood. The table below summarizes the houses tested.

Table 22 – Houses Tested

House ID	Approach	# Similar	Gross Area	Bedrooms
Banning A	Cathedralized Attic	8	1675	2
Banning B	Cathedralized Attic	1	2139	2/3
Cottonwood	Dropped Ceiling	1	3150	2/3
El Dorado Hills	Cathedralized Attic	1	2873	3/4
Livermore	Cathedralized Attic	1	2650	3/4
Mt. Shasta A	Dropped Ceiling	1	1600	3
Mt. Shasta B	Dropped Ceiling	1	1485	2/3
Mt. Shasta C	Dropped Ceiling	1	1550	3
Redding	Cathedralized Attic	1	2500	2/3

Note: 2/3 or 3/4 bedrooms indicates 2 (or 3) bedrooms plus a den.

Summary of Test Data

The table below summarizes the results of duct leakage tests, including total duct leakage and leakage to the outside, with the attic hatch closed. The fraction of total duct leakage that goes to outside is also shown.

The data are also summarized for all tested houses, and also segregated by approach. Note that in all cases, duct leakage is quite low. The Cathedralized Attic houses have slightly lower duct leakage, but of that leakage, 61% goes to the outside. The Dropped Ceiling houses, while they have slightly higher leakage, have lower leakage to the outside, about 33% of the total leakage. This seems to make sense, intuitively, in that the Cathedralized Attic has much greater surface area exposed to the outdoors and therefore many more opportunities for leaks. The Dropped Ceiling has only the top of the hallway dropped ceiling area that needs to be sealed, minimizing the possible leakage sites.

Table 23 – Duct Leakage Test Results

House ID	Type	Duct Leakage[1] (cfm @ 25 Pa)	Leak to Outside[1] (cfm @ 25Pa)	(%)
Banning A-2	Cathedralized Attic	42	15	36%
Banning A-3	Cathedralized Attic	28	17	61%
Banning A-4	Cathedralized Attic	52	38	73%
Banning B	Cathedralized Attic	49	30	61%
Banning A-5	Cathedralized Attic	41	29	71%
Banning A-6	Cathedralized Attic	47	22	47%
Banning A-7	Cathedralized Attic	49	40	82%
Banning A-8	Cathedralized Attic	46	27	59%
Banning A-9	Cathedralized Attic	48	21	44%
Cottonwood	Dropped Ceiling	41	6	15%
El Dorado Hills	Cathedralized Attic	91	70	77%
Livermore	Cathedralized Attic	50	32	64%
Mt. Shasta A	Dropped Ceiling	76	30	39%
Mt. Shasta B	Dropped Ceiling	68	22	32%
Mt. Shasta C	Dropped Ceiling	55	25	45%
Redding	Cathedralized Attic	68	44	65%
All Houses:	**Average[2]**	**52**	**29**	**55%**
	Minimum[2]	28	6	15%
	Maximum[2]	91	70	82%
Cathedralized Attic Only:	**Average[2]**	**49**	**31**	**61%**
	Minimum[2]	28	15	36%
	Maximum[2]	91	70	82%
Dropped Ceiling Only:	**Average[2]**	**60**	**21**	**33%**
	Minimum[2]	41	6	15%
	Maximum[2]	76	30	45%

[1] Duct leakage includes both supply and return sides of the system.
[2] The three Average (and Minimum and Maximum) values may represent different houses.

Analytical Approach

The energy savings estimates were developed using DOE-2 simulations. A version of DOE-2.1E released by James J. Hirsch and Associates which includes keywords that allow simulation of the effects of duct leakage was used.

Three house designs were modeled, each of which were described previously in Deliverable 6.3.3, Identification of Representative House Designs. That report identified nine designs, and for the energy simulations (as well as the cost estimates in Deliverable 6.5.2) we used designs 2, 5 and 8. These houses are a 1,746 ft² single story house, a 3,148 ft² two story house, and a 1,216 ft² two story townhouse. Two baseline variants were developed. A "normal" leakage case used duct leakage of 22% of system flow, split between supply and return. The normal case is typical of a house built with normal construction techniques. A “low” leakage case used leakage of 6% of system flow that represents a home built to receive the Title 24 ACM credit.

The California Building Industry Association’s website provides data on housing starts for the state as a whole and for 23 metropolitan or county areas. The climate zone or zones for each of the 23 areas was identified. These covered 12 of the 16 climate zones in California. In addition, many of the tested houses were located in a 13th climate zone (CZ 15). Based on this, simulations were performed using weather data for the 13 climate zones. (See Appendix A for the housing data used.) The house envelope characteristics (wall insulation, roof insulation, glazing U-factor and solar heat gain coefficient) were adjusted for each climate zone as specified in Title 24, Prescriptive Package D. These variations are shown in the table below. In all cases, the system modeled was a gas furnace with electric air conditioner, with equipment capacity determined by DOE-2 sizing algorithms.

Table 24 – Modeled Envelope Characteristics by Climate Zone

	Insulation (R value)		Glazing	
Climate Zone	Wall	Ceiling	U-factor	SHGC
2	R13	R30	0.65	0.40
3	R13	R30	0.75	0.60*
4	R13	R30	0.75	0.40
5	R13	R30	0.75	0.60*
6	R13	R30	0.75	0.60*
7	R13	R30	0.75	0.40
8	R13	R30	0.75	0.40
9	R13	R30	0.75	0.40
10	R13	R30	0.65	0.40
11	R19	R38	0.65	0.40
12	R19	R38	0.65	0.40
13	R19	R38	0.65	0.40
15	R21	R38	0.65	0.40

* SHGC is not specified for these climate zones, 0.60 was used.

The cases using ducts in conditioned space were modeled by adding a duct space zone (dropped ceiling and plenum truss approaches) or by relocating the roof insulation and adjusting attic infiltration (cathedralized attic approach). Duct leakage for the conditioned space cases was adjusted from the low leakage case. For the Cathedralized Attic cases, duct leakage was set to 4% (61% of the 6% base case value). For the Dropped Ceiling cases, leakage was set to 2% (33% of 6%). This provided a total of five cases per house per location. With three houses and 13 locations, a total of 195 runs were performed.

Annual Energy Savings

Runs for climate zone 4 would not run. The cause of this problem was unknown. The DOE-2 results (energy consumption estimates) for the remaining 12 climate zones are shown in Appendix B. The tables below show the energy and demand savings for each approach compared to the high or low leakage base cases, both in energy units and as percentage savings.

**Table 25 – Annual Energy Savings
Cathedralized Attic vs. Normal Leakage Base Case**

Climate Zone	House Type	Cooling Elec. (kWh)	Cooling Elec. (%)	Total Electric (kWh)	Total Electric (%)	Peak Electric (kW)	Peak Electric (%)	Total Gas (therms)	Total Gas (%)
2	Two-Story	2,110	32	2,139	7	1.0	10	-68	-14
2	One-Story	1,231	34	1,231	7	0.7	12	12	2
2	Townhouse	645	32	674	5	0.3	7	-28	-11
3	Two-Story	2,608	37	2,666	9	0.8	9	-61	-21
3	One-Story	1,348	37	1,377	8	0.5	10	-12	-4
3	Townhouse	703	37	732	6	0.3	7	-27	-13
5	Two-Story	2,901	38	2,959	10	0.7	8	-46	-24
5	One-Story	1,377	36	1,406	8	0.4	9	-14	-6
5	Townhouse	732	37	732	6	0.2	6	-26	-14
6	Two-Story	4,043	33	4,102	12	0.8	9	-10	-7
6	One-Story	2,227	34	2,256	12	0.5	9	-6	-4
6	Townhouse	1,084	34	1,113	8	0.3	6	-11	-8
7	Two-Story	2,783	33	2,813	9	0.6	7	-21	-14
7	One-Story	1,465	34	1,494	9	0.4	8	-12	-7
7	Townhouse	850	33	850	6	0.2	5	-13	-9
8	Two-Story	3,018	31	3,047	10	0.8	9	-24	-14
8	One-Story	1,758	32	1,817	10	0.7	13	-9	-5
8	Townhouse	908	31	938	7	0.2	6	-13	-8
9	Two-Story	3,282	31	3,282	10	1.8	17	-24	-14
9	One-Story	1,963	33	1,963	10	1.1	19	-10	-5
9	Townhouse	967	31	938	7	0.5	12	-15	-10
10	Two-Story	3,750	30	3,721	11	0.9	9	-30	-17
10	One-Story	2,256	31	2,256	11	0.9	15	-11	-5
10	Townhouse	1,025	29	1,055	7	0.3	7	-16	-10
11	Two-Story	3,106	29	3,076	9	2.0	17	-59	-11
11	One-Story	1,963	30	1,963	10	1.3	19	-2	0
11	Townhouse	938	30	908	6	0.6	12	-27	-10
12	Two-Story	2,871	31	2,871	9	1.5	14	-62	-13
12	One-Story	1,758	32	1,758	10	1.1	17	-6	-1
12	Townhouse	850	31	850	6	0.3	8	-27	-11
13	Two-Story	3,809	28	3,809	11	2.4	20	-50	-14
13	One-Story	2,520	30	2,549	12	1.3	20	-5	-1
13	Townhouse	1,143	28	1,113	7	0.7	15	-22	-11
15	Two-Story	7,735	32	7,618	16	3.3	25	-4	-3
15	One-Story	5,215	34	5,186	18	1.8	24	-4	-3
15	Townhouse	2,227	32	2,168	12	1.1	20	-3	-2

**Table 26 – Annual Energy Savings
Dropped Ceiling vs. High Leakage Base Case**

Climate Zone	House Type	Cooling Elec. (kWh)	Cooling Elec. (%)	Total Electric (kWh)	Total Electric (%)	Peak Electric (kW)	Peak Electric (%)	Total Gas (therms)	Total Gas (%)
2	Two-Story	1,963	30	1,963	7	1.2	12	63	13
2	One-Story	1,113	31	1,113	7	0.8	14	81	16
2	Townhouse	615	31	615	5	0.4	9	23	9
3	Two-Story	1,992	28	1,992	7	0.8	9	26	9
3	One-Story	996	28	996	6	0.5	10	42	13
3	Townhouse	557	29	557	4	0.3	7	13	6
5	Two-Story	2,168	28	2,227	7	0.7	9	10	5
5	One-Story	1,025	27	1,055	6	0.4	9	28	12
5	Townhouse	557	28	557	4	0.3	7	8	4
6	Two-Story	3,516	29	3,545	10	0.9	10	0	0
6	One-Story	1,875	28	1,875	10	0.5	10	6	4
6	Townhouse	908	29	938	7	0.3	7	1	1
7	Two-Story	2,373	28	2,403	8	0.7	9	2	1
7	One-Story	1,231	29	1,231	7	0.4	8	12	7
7	Townhouse	732	29	762	6	0.2	6	1	1
8	Two-Story	2,842	29	2,842	9	0.9	10	5	3
8	One-Story	1,582	29	1,611	9	0.8	14	16	8
8	Townhouse	850	29	879	6	0.3	7	3	2
9	Two-Story	3,135	30	3,106	10	1.9	19	5	3
9	One-Story	1,817	30	1,817	10	1.2	20	17	9
9	Townhouse	908	30	879	6	0.6	13	2	1
10	Two-Story	3,692	30	3,662	11	1.1	11	8	4
10	One-Story	2,168	30	2,168	11	1.1	17	19	9
10	Townhouse	1,025	29	1,025	7	0.4	9	5	3
11	Two-Story	3,164	30	3,164	10	2.2	19	70	13
11	One-Story	1,934	30	1,904	10	1.5	21	78	15
11	Townhouse	938	30	908	6	0.6	13	22	8
12	Two-Story	2,783	30	2,783	9	1.6	15	58	12
12	One-Story	1,611	30	1,611	9	1.1	18	68	14
12	Townhouse	820	29	820	6	0.4	9	19	8
13	Two-Story	4,014	29	4,043	11	2.6	22	37	11
13	One-Story	2,549	31	2,549	12	1.5	21	48	13
13	Townhouse	1,201	29	1,201	8	0.8	16	11	5
15	Two-Story	8,263	34	8,145	17	3.5	26	0	0
15	One-Story	5,479	36	5,420	19	2.0	25	2	1
15	Townhouse	2,344	34	2,285	13	1.2	22	0	0

Table 27 – Annual Energy Savings
Plenum Truss vs. Normal Leakage Base Case

Climate Zone	House Type	Cooling Elec. (kWh)	Cooling Elec. (%)	Total Electric (kWh)	Total Electric (%)	Peak Electric (kW)	Peak Electric (%)	Total Gas (therms)	Total Gas (%)
2	Two-Story	1,904	29	1,904	7	1.1	11	-6	-1
2	One-Story	1,025	28	996	6	0.8	13	53	10
2	Townhouse	557	28	557	4	0.3	8	0	0
3	Two-Story	2,139	30	2,139	7	0.8	9	-16	-5
3	One-Story	938	26	938	6	0.5	10	26	8
3	Townhouse	557	29	557	4	0.3	6	-6	-3
5	Two-Story	2,403	31	2,461	8	0.7	8	-14	-7
5	One-Story	1,025	27	1,055	6	0.4	8	18	8
5	Townhouse	586	30	586	4	0.2	6	-7	-4
6	Two-Story	3,633	30	3,633	11	0.8	9	-3	-2
6	One-Story	1,817	27	1,817	9	0.5	9	4	3
6	Townhouse	938	30	967	7	0.3	7	-3	-2
7	Two-Story	2,403	29	2,432	8	0.6	7	-6	-4
7	One-Story	1,143	27	1,143	7	0.4	8	8	4
7	Townhouse	703	28	732	5	0.2	6	-5	-3
8	Two-Story	2,754	28	2,754	9	0.9	9	-7	-4
8	One-Story	1,465	27	1,494	8	0.7	14	10	5
8	Townhouse	820	28	820	6	0.3	6	-3	-2
9	Two-Story	3,047	29	3,047	9	1.8	18	-6	-4
9	One-Story	1,699	28	1,699	9	1.2	20	12	6
9	Townhouse	879	29	850	6	0.5	12	-4	-3
10	Two-Story	3,545	28	3,545	10	1.0	10	-7	-4
10	One-Story	2,051	28	2,022	10	1.0	16	13	6
10	Townhouse	967	28	967	7	0.3	8	-3	-2
11	Two-Story	2,959	28	2,959	9	2.1	18	11	2
11	One-Story	1,787	28	1,758	9	1.4	20	57	11
11	Townhouse	879	28	850	6	0.6	12	3	1
12	Two-Story	2,666	28	2,637	8	1.5	14	3	1
12	One-Story	1,494	28	1,494	8	1.1	17	49	10
12	Townhouse	762	27	762	5	0.4	8	1	0
13	Two-Story	3,721	27	3,721	10	2.5	21	-5	-1
13	One-Story	2,344	28	2,344	11	1.4	21	33	9
13	Townhouse	1,113	27	1,084	7	0.7	15	-2	-1
15	Two-Story	7,852	32	7,735	16	3.4	25	-1	-1
15	One-Story	5,186	34	5,157	18	1.9	25	2	1
15	Townhouse	2,227	32	2,168	12	1.1	21	-1	-1

**Table 28 – Annual Energy Savings
Cathedralized Attic vs. Low Leakage Base Case**

Climate Zone	House Type	Cooling Elec. (kWh)	Cooling Elec. (%)	Total Electric (kWh)	Total Electric (%)	Peak Electric (kW)	Peak Electric (%)	Total Gas (therms)	Total Gas (%)
2	Two-Story	732	14	732	3	0.2	2	-138	-33
2	One-Story	469	16	469	3	0.2	3	-62	-14
2	Townhouse	205	13	234	2	0.0	1	-53	-22
3	Two-Story	1,260	22	1,289	5	0.2	3	-91	-35
3	One-Story	645	22	674	4	0.1	3	-47	-17
3	Townhouse	322	21	352	3	0.1	2	-41	-21
5	Two-Story	1,406	23	1,436	5	0.2	2	-57	-32
5	One-Story	674	22	674	4	0.1	3	-33	-15
5	Townhouse	352	22	352	3	0.1	2	-35	-20
6	Two-Story	1,582	16	1,611	5	0.2	2	-10	-7
6	One-Story	908	17	908	5	0.1	3	-9	-6
6	Townhouse	439	17	439	3	0.1	2	-12	-8
7	Two-Story	1,143	17	1,143	4	0.1	1	-23	-15
7	One-Story	645	18	645	4	0.1	2	-19	-11
7	Townhouse	322	16	322	2	0.0	1	-14	-10
8	Two-Story	1,055	13	1,055	4	0.2	2	-30	-18
8	One-Story	703	16	703	4	0.3	5	-20	-11
8	Townhouse	322	14	322	2	0.0	1	-16	-11
9	Two-Story	1,172	14	1,143	4	0.8	8	-30	-19
9	One-Story	762	16	732	4	0.4	8	-21	-11
9	Townhouse	322	13	322	2	0.3	6	-17	-11
10	Two-Story	1,143	12	1,113	3	0.0	0	-38	-22
10	One-Story	762	13	762	4	0.3	6	-24	-12
10	Townhouse	293	11	322	2	0.0	1	-21	-13
11	Two-Story	879	10	850	3	0.6	6	-138	-30
11	One-Story	645	13	674	4	0.3	6	-76	-17
11	Townhouse	264	11	264	2	0.2	5	-52	-22
12	Two-Story	908	12	908	3	0.4	4	-128	-31
12	One-Story	645	15	645	4	0.3	5	-71	-18
12	Townhouse	264	12	264	2	0.1	1	-49	-22
13	Two-Story	1,025	9	967	3	0.8	8	-92	-30
13	One-Story	820	12	820	4	0.5	8	-49	-15
13	Townhouse	293	9	264	2	0.3	6	-34	-18
15	Two-Story	2,285	12	2,197	5	0.6	6	-4	-3
15	One-Story	1,641	14	1,611	7	0.3	5	-5	-3
15	Townhouse	674	13	645	4	0.2	5	-3	-2

**Table 29 – Annual Energy Savings
Dropped Ceiling vs. Low Leakage Base Case**

Climate Zone	House Type	Cooling Elec. (kWh)	Cooling Elec. (%)	Total Electric (kWh)	Total Electric (%)	Peak Electric (kW)	Peak Electric (%)	Total Gas (therms)	Total Gas (%)
2	Two-Story	586	11	557	2	0.3	4	-7	-2
2	One-Story	352	12	352	2	0.2	5	7	2
2	Townhouse	176	11	176	1	0.1	3	-2	-1
3	Two-Story	645	11	615	2	0.2	3	-4	-2
3	One-Story	293	10	293	2	0.2	3	7	2
3	Townhouse	176	12	176	1	0.1	2	-1	-1
5	Two-Story	674	11	703	2	0.2	3	-1	-1
5	One-Story	322	10	322	2	0.1	3	9	4
5	Townhouse	176	11	176	1	0.1	2	-1	-1
6	Two-Story	1,055	11	1,055	3	0.3	3	0	0
6	One-Story	557	10	527	3	0.2	3	3	2
6	Townhouse	264	10	264	2	0.1	2	0	0
7	Two-Story	732	11	732	3	0.2	3	0	0
7	One-Story	410	12	381	2	0.1	3	5	3
7	Townhouse	205	10	234	2	0.1	2	0	0
8	Two-Story	879	11	850	3	0.3	4	-1	-1
8	One-Story	527	12	498	3	0.3	6	5	3
8	Townhouse	264	11	264	2	0.1	2	0	0
9	Two-Story	1,025	12	967	3	0.9	10	-1	-1
9	One-Story	615	13	586	3	0.5	10	6	3
9	Townhouse	264	11	264	2	0.3	8	0	0
10	Two-Story	1,084	11	1,055	3	0.3	3	0	0
10	One-Story	674	12	674	4	0.4	8	6	3
10	Townhouse	293	11	293	2	0.1	3	0	0
11	Two-Story	938	11	938	3	0.8	8	-9	-2
11	One-Story	615	12	615	3	0.5	8	4	1
11	Townhouse	264	11	264	2	0.3	6	-3	-1
12	Two-Story	820	11	820	3	0.6	6	-8	-2
12	One-Story	498	12	498	3	0.4	6	3	1
12	Townhouse	234	11	234	2	0.1	3	-3	-1
13	Two-Story	1,231	11	1,201	4	1.0	10	-5	-2
13	One-Story	850	13	820	4	0.6	10	4	1
13	Townhouse	352	11	352	2	0.3	7	-1	-1
15	Two-Story	2,813	15	2,725	7	0.9	8	0	0
15	One-Story	1,904	16	1,846	7	0.4	7	1	1
15	Townhouse	791	15	762	5	0.3	6	0	0

Table 30 – Annual Energy Savings
Plenum Truss vs. Low Leakage Base Case

Climate Zone	House Type	Cooling Elec. (kWh)	Cooling Elec. (%)	Total Electric (kWh)	Total Electric (%)	Peak Electric (kW)	Peak Electric (%)	Total Gas (therms)	Total Gas (%)
2	Two-Story	527	10	498	2	0.2	3	-76	-18
2	One-Story	264	9	234	1	0.2	4	-21	-5
2	Townhouse	117	8	117	1	0.1	2	-25	-10
3	Two-Story	791	14	762	3	0.2	3	-46	-18
3	One-Story	234	8	234	1	0.1	3	-9	-3
3	Townhouse	176	12	176	1	0.1	2	-20	-10
5	Two-Story	908	15	938	3	0.2	2	-25	-14
5	One-Story	322	10	322	2	0.1	2	-1	0
5	Townhouse	205	13	205	2	0.1	2	-16	-9
6	Two-Story	1,172	12	1,143	4	0.2	2	-3	-2
6	One-Story	498	9	469	3	0.1	2	1	1
6	Townhouse	293	12	293	2	0.1	2	-4	-3
7	Two-Story	762	11	762	3	0.1	1	-8	-5
7	One-Story	322	9	293	2	0.1	2	1	1
7	Townhouse	176	9	205	2	0.0	1	-6	-4
8	Two-Story	791	10	762	3	0.2	3	-13	-8
8	One-Story	410	9	381	2	0.3	6	-1	-1
8	Townhouse	234	10	205	2	0.0	1	-6	-4
9	Two-Story	938	11	908	3	0.8	9	-12	-7
9	One-Story	498	10	469	3	0.5	9	1	1
9	Townhouse	234	10	234	2	0.3	7	-6	-4
10	Two-Story	938	9	938	3	0.1	1	-15	-9
10	One-Story	557	10	527	3	0.4	7	0	0
10	Townhouse	234	9	234	2	0.1	2	-8	-5
11	Two-Story	732	9	732	2	0.7	7	-68	-15
11	One-Story	469	9	469	3	0.4	7	-17	-4
11	Townhouse	205	8	205	2	0.2	5	-22	-9
12	Two-Story	703	9	674	2	0.5	5	-63	-15
12	One-Story	381	9	381	2	0.3	6	-16	-4
12	Townhouse	176	8	176	1	0.1	2	-21	-9
13	Two-Story	938	9	879	3	0.9	9	-47	-15
13	One-Story	645	10	615	3	0.5	9	-11	-3
13	Townhouse	264	8	234	2	0.3	7	-14	-7
15	Two-Story	2,403	13	2,315	6	0.7	7	-1	-1
15	One-Story	1,611	14	1,582	6	0.4	6	1	1
15	Townhouse	674	13	645	4	0.2	5	-1	-1

The energy savings shown above vary significantly by climate, house type and baseline. In order to summarize the savings, the 2002 housing start data was used to develop weighting factors. Table 31 shows the weighting factors for single family and multifamily housing by climate zone (see Appendix A for additional data).

Table 31 – 2002 Housing Starts by Climate Zone and Statewide Weighting Factors

	2002 Housing Starts		Weighting Factors	
Climate Zn.	**Single Family**	**Multifamily**	**Single Family**	**Multifamily**
2	2,269	1,008	1.9%	3.0%
3	11,108	4,275	9.1%	12.7%
4	2,122	2,502	1.7%	7.4%
5	2,355	722	1.9%	2.1%
6	3,792	2,614	3.1%	7.8%
7	4,432	2,300	3.6%	6.8%
8	7,568	6,058	6.2%	18.0%
9	4,084	3,669	3.3%	10.9%
10	34,300	5,035	28.1%	15.0%
11	2,356	145	1.9%	0.4%
12	28,259	5,839	23.2%	17.4%
13	10,504	696	8.6%	2.1%
15	8,905	0	7.3%	0.0%
Total	122,053	33,633		

Using the weighting factors developed above, the savings for each climate zone were combined into a single statewide average. These results are shown below in Tables 32 and 33, along with the maximum value from any climate zone.

Table 32 – Weighted Average and Maximum Savings vs. Normal Leakage Base Case by Approach and House Type

Approach	**House**		**Cooling Electric (kWh)**	**Total Electric (kWh**	**Peak Electric (kW)**	**Total Gas (therms)**
Cathedralized Attic	Two Story	Avg	3,527	3,521	1	-40
		Max	7,735	7,618	3	-4
	One Story	Avg	2,145	2,155	1	-8
		Max	5,215	5,186	2	12
	Townhouse	Avg	865	877	0	-18
		Max	2,227	2,168	1	-3
Dropped Ceiling	Two Story	Avg	3,427	3,415	1	24
		Max	8,263	8,145	4	70
	One Story	Avg	2,032	2,029	1	35
		Max	5,479	5,420	2	81
	Townhouse	Avg	799	805	0	8
		Max	2,344	2,285	1	23
Plenum Truss	Two Story	Avg	3,313	3,300	1	-4
		Max	7,852	7,735	3	11
	One Story	Avg	1,907	1,898	1	24
		Max	5,186	5,157	2	57
	Townhouse	Avg	768	769	0	-3
		Max	2,227	2,168	1	3

Table 33 – Weighted Average and Maximum Savings vs. Low Leakage Base Case by Approach and House Type

Approach	House		Cooling Electric (kWh)	Total Electric (kWh)	Peak Electric (kW)	Total Gas (therms)
Cathedralized Attic	Two Story	Avg	1,154	1,137	0	-67
		Max	2,285	2,197	1	-4
	One Story	Avg	767	767	0	-38
		Max	1,641	1,611	0	-5
	Townhouse	Avg	301	309	0	-27
		Max	674	645	0	-3
Dropped Ceiling	Two Story	Avg	1,055	1,031	0	-3
		Max	2,813	2,725	1	0
	One Story	Avg	654	642	0	5
		Max	1,904	1,846	1	9
	Townhouse	Avg	235	237	0	-1
		Max	791	762	0	0
Plenum Truss	Two Story	Avg	940	916	0	-32
		Max	2,403	2,315	1	-1
	One Story	Avg	528	510	0	-6
		Max	1,611	1,582	1	1
	Townhouse	Avg	205	201	0	-11
		Max	674	645	0	-1

Table 34 shows the minimum, maximum and average savings per construction approach for each housing type, duct leakage and climate zone.

Table 34. Range of Energy Savings by Housing Type, Duct Leakage and Climate Zone (CZ)

Cathedralized Attic							
House Type		**Two-story**		**one-story**		**townhouse**	
Duct Leakage		**Low**	**Normal**	**Low**	**Normal**	**low**	**normal**
Elec. (KWh per house)	Ave	1,137	3,521	767	2,155	309	877
	Max	2,197	7,618	1,611	5,186	645	2,168
	Max CZ	15	15	15	15	15	15
	Min	732	2,139	469	1,231	234	674
	Min CZ	2	2	2	2	2	2
Nat Gas (Therm per house)	Ave	-67	-40	-38	-8	-27	-18
	Max	-4	-4	-5	-4	-3	-3
	Max CZ	15	15	15	15	15	12
	Min	-138	-68	-76	-68	-53	-28
	Min CZ	2 & 11	2	11	2	2	2

Dropped Ceiling							
House Type		**Two-story**		**one-story**		**townhouse**	
Duct Leakage		**Low**	**Normal**	**Low**	**Normal**	**low**	**normal**
Elec. (KWh per house)	Ave	1,031	3,415	642	2,029	237	805
	Max	2,725	8,145	1,846	5,420	762	2,285
	Max CZ	15	15	15	15	15	15
	Min	557	1,963	293	996	175	557
	Min CZ	2	2	3	3	2,3,5	3 & 5
Nat Gas (Therm per house)	Ave	-3	24	5	35	-1	8
	Max	0	70	9	81	0	23
	Max CZ	6,7,10,15	11	5	2	6,7,9,10,15	2
	Min	-7	0	1	2	-3	0
	Min CZ	2	6 & 15	15	15	11	15

Plenum Truss							
House Type		**Two-story**		**one-story**		**townhouse**	
Duct Leakage		**Low**	**Normal**	**Low**	**Normal**	**low**	**normal**
Elec. (KWh per house)	Ave	916	3,300	510	1,898	201	769
	Max	2,315	7,735	1,582	5,157	645	2,168
	Max CZ	15	15	15	15	15	15
	Min	498	1,904	234	938	117	557
	Min CZ	2	2	2,3	3	2	2 & 3
Nat Gas (Therm per house)	Ave	-32	-4	-6	24	-11	-3
	Max	-1	11	1	57	-1	3
	Max CZ	15	11	6,7,9,15	11	-1	11
	Min	-18	-16	-4	2	-10	-7
	Min CZ	2	3	11	15	2	5

Statewide Energy Impact

Using the energy savings by climate zone and house type, along with the data on new housing starts, the statewide energy impact of programs encouraging the adoption of building houses with ducts in conditioned space can be estimated. For each climate zone with significant building activity, Table 31 gives the number of new housing starts for single family and multifamily units. Tables 25 through 30 give the energy savings for each of three houses (two story, one story and townhouse) in each climate zone for each approach.

The statewide energy savings are then estimated by applying assumptions about the market penetration of building ducts in conditioned space, as well as the relative penetration of each approach.

First, of the new single family homes, 30% are assumed to be large homes best represented by the two story model, and 70% are smaller, best represented by the one story model. The townhouse model is assumed to represent all of the multifamily houses.

Of all the houses that are built with ducts in conditioned space, it is assumed that 5% use the plenum truss approach. Of the multifamily houses, it is assumed that 65% use the cathedralized attic approach, and 30% use the dropped ceiling approach. Of the one story houses, it is assumed that 40% use the dropped ceiling approach and 55% use the cathedralized attic. For the two story houses, the assumption is 60% dropped ceiling and 35% cathedralized attic.

Overall market penetration was assumed for a ten year period. The percent of new houses built with some form of ducts in conditioned space is shown in Table 34 below, along with the number of houses this fraction represents.

Table 34 – Assumed Market Penetration of Houses Built with Ducts in Conditioned Space

Year	Yr 1	Yr 2	Yr 3	Yr 4	Yr 5	Yr 6	Yr 7	Yr 8	Yr 9	Yr 10
% of New Homes	0.1%	0.2%	0.5%	0.7%	1%	1.5%	2%	4%	6%	10%
# of New Homes	152	305	761	1,066	1,523	2,284	3,046	6,092	9,138	15,229

Using the factors above, the energy savings for each of the ten years included in Table 34 were calculated. The savings were computed for both electricity and gas, for both the low leakage and normal leakage base cases. The savings for each year also include the savings for each previous year, because the energy savings for houses built in a given year continue to accrue throughout the life of the house. Table 35 shows the overall energy savings for year 10, with the overall average based on an assumption that 30% of new houses will have low leakage duct systems, and 70% will have normal leakage.

Table 35 – Estimated Annual Statewide Energy Savings for Ducts in Conditioned Space after Ten Years

	Annual Energy Savings in Year 10	
	Electric (MWh)	Gas (1000 therms)
Normal Leakage Base Case	86,711	162
Low Leakage Base Case	28,227	-848
Overall Average	69,166	-141

Energy Cost Savings

Once energy savings were determined, residential gas and electric rates of major utilities in California were investigated. For savings estimates, we are interested in marginal rates. Utilities used were Pacific Gas and Electric, Sacramento Municipal Utility District, Southern California Edison, Southern California Gas, and San Diego Gas and Electric. The electric and gas rates found are shown in Tables 36 and 37, respectively below.

The rate varies significantly depending on the total energy consumption level of the house, particularly for electricity. Comparing the various baseline levels to the predicted energy consumption levels from Appendix B, the energy savings were calculated using the top tier summer electric rate and the baseline gas rate. Climate zones and utility service areas do not coincide, but results by climate were assigned to the different utilities based on the predominant utility serving that climate zone. Climate zone 12 used SMUD electric rates and PGE gas rates, climate zones 7 and 15 used SDG&E rates, climate zones 2, 3, 11 and 13 used PG&E rates, and climate zones 5, 6, 8, 9 and 10 used SoCal Edison electric rates and SoCal Gas gas rates.

None of the utilities had residential demand rates, so no cost savings attached to the demand reductions.

Table 36 – Residential Electric Rates – Selected California Utilities

	Rate Step	$/kWh
PG&E	Baseline	0.12589
	101 to 130% of Baseline	0.14321
	131 to 200% of Baseline	0.19445
	201 to 300% of Baseline	0.23838
	More than 300% of Baseline	0.25826
SMUD	Winter Baseline Tier I	0.07378
	Winter Tier II	0.12995
	Winter Tier III	0.14231
	Summer Baseline Tier I	0.08058
	Summer Tier II	0.13965
	Summer Tier III	0.15688
	Surcharge on all rates	0.00263
SoCal Edison	Baseline	0.13009
	101 to 130% of Baseline	0.15157
	131 to 200% of Baseline	0.19704
	201 to 300% of Baseline	0.23645
	More than 300% of Baseline	0.25993
SDG&E	Baseline	0.07247
	Winter Excess	0.15013
	Summer Excess	0.15780

Table 37 – Residential Gas Rates – Selected California Utilities

	Rate Step	$/therm
PG&E	Baseline	0.84956
	Excess	1.06513
SoCal Gas	Baseline	0.75708
	Non-Baseline	0.93859
SDG&E	Residential	0.97875

Table 38 – Annual Energy Cost Savings - Cathedralized Attic

Climate Zone	House Type	Utility Rate		Vs. Normal Leakage Base			Vs. Low Leakage Base		
		Elec. ($/kWh)	Gas ($/therm)	Electric ($)	Gas ($)	Total ($)	Electric ($)	Gas ($)	Total ($)
2	Two-Story	0.25826	0.84956	552	-58	**495**	189	-117	**72**
2	One-Story	0.25826	0.84956	318	10	**328**	121	-53	**68**
2	Townhouse	0.25826	0.84956	174	-24	**150**	61	-45	**16**
3	Two-Story	0.25826	0.84956	689	-52	**637**	333	-77	**256**
3	One-Story	0.25826	0.84956	356	-10	**345**	174	-40	**134**
3	Townhouse	0.25826	0.84956	189	-23	**166**	91	-35	**56**
5	Two-Story	0.25993	0.75708	769	-35	**734**	373	-43	**330**
5	One-Story	0.25993	0.75708	366	-11	**355**	175	-25	**150**
5	Townhouse	0.25993	0.75708	190	-20	**171**	91	-26	**65**
6	Two-Story	0.25993	0.75708	1066	-8	**1059**	419	-8	**411**
6	One-Story	0.25993	0.75708	586	-5	**582**	236	-7	**229**
6	Townhouse	0.25993	0.75708	289	-8	**281**	114	-9	**105**
7	Two-Story	0.1578	0.97875	444	-21	**423**	180	-23	**158**
7	One-Story	0.1578	0.97875	236	-12	**224**	102	-19	**83**
7	Townhouse	0.1578	0.97875	134	-13	**121**	51	-14	**37**
8	Two-Story	0.25993	0.75708	792	-18	**774**	274	-23	**251**
8	One-Story	0.25993	0.75708	472	-7	**465**	183	-15	**168**
8	Townhouse	0.25993	0.75708	244	-10	**234**	84	-12	**72**
9	Two-Story	0.25993	0.75708	853	-18	**835**	297	-23	**274**
9	One-Story	0.25993	0.75708	510	-8	**503**	190	-16	**174**
9	Townhouse	0.25993	0.75708	244	-11	**232**	84	-13	**71**
10	Two-Story	0.25993	0.75708	967	-23	**945**	289	-29	**261**
10	One-Story	0.25993	0.75708	586	-8	**578**	198	-18	**180**
10	Townhouse	0.25993	0.75708	274	-12	**262**	84	-16	**68**
11	Two-Story	0.25826	0.84956	795	-50	**744**	219	-117	**102**
11	One-Story	0.25826	0.84956	507	-2	**505**	174	-65	**109**
11	Townhouse	0.25826	0.84956	235	-23	**212**	68	-44	**24**
12	Two-Story	0.15951	0.84956	458	-53	**405**	145	-109	**36**
12	One-Story	0.15951	0.84956	280	-5	**275**	103	-60	**43**
12	Townhouse	0.15951	0.84956	136	-23	**113**	42	-42	**0**
13	Two-Story	0.25826	0.84956	984	-42	**941**	250	-78	**172**
13	One-Story	0.25826	0.84956	658	-4	**654**	212	-42	**170**
13	Townhouse	0.25826	0.84956	288	-19	**269**	68	-29	**39**
15	Two-Story	0.1578	0.97875	1202	-4	**1198**	347	-4	**343**
15	One-Story	0.1578	0.97875	818	-4	**814**	254	-5	**249**
15	Townhouse	0.1578	0.97875	342	-3	**339**	102	-3	**99**

Table 39 – Annual Energy Cost Savings - Dropped Ceiling

Climate Zone	House Type	Utility Rate		Vs. Normal Leakage Base			Vs. Low Leakage Base		
		Elec. ($/kWh)	Gas ($/therm)	Electric ($)	Gas ($)	Total ($)	Electric ($)	Gas ($)	Total ($)
2	Two-Story	0.25826	0.84956	507	54	**561**	144	-6	**138**
2	One-Story	0.25826	0.84956	288	69	**356**	91	6	**97**
2	Townhouse	0.25826	0.84956	159	20	**178**	45	-2	**44**
3	Two-Story	0.25826	0.84956	515	22	**537**	159	-3	**156**
3	One-Story	0.25826	0.84956	257	36	**293**	76	6	**82**
3	Townhouse	0.25826	0.84956	144	11	**155**	45	-1	**45**
5	Two-Story	0.25993	0.75708	579	8	**586**	183	-1	**182**
5	One-Story	0.25993	0.75708	274	21	**295**	84	7	**91**
5	Townhouse	0.25993	0.75708	145	6	**151**	46	-1	**45**
6	Two-Story	0.25993	0.75708	922	0	**922**	274	0	**274**
6	One-Story	0.25993	0.75708	487	5	**492**	137	2	**139**
6	Townhouse	0.25993	0.75708	244	1	**244**	69	0	**69**
7	Two-Story	0.1578	0.97875	379	2	**381**	116	0	**116**
7	One-Story	0.1578	0.97875	194	12	**206**	60	5	**65**
7	Townhouse	0.1578	0.97875	120	1	**121**	37	0	**37**
8	Two-Story	0.25993	0.75708	739	4	**743**	221	-1	**220**
8	One-Story	0.25993	0.75708	419	12	**431**	129	4	**133**
8	Townhouse	0.25993	0.75708	228	2	**231**	69	0	**69**
9	Two-Story	0.25993	0.75708	807	4	**811**	251	-1	**251**
9	One-Story	0.25993	0.75708	472	13	**485**	152	5	**157**
9	Townhouse	0.25993	0.75708	228	2	**230**	69	0	**69**
10	Two-Story	0.25993	0.75708	952	6	**958**	274	0	**274**
10	One-Story	0.25993	0.75708	564	14	**578**	175	5	**180**
10	Townhouse	0.25993	0.75708	267	4	**270**	76	0	**76**
11	Two-Story	0.25826	0.84956	817	59	**877**	242	-8	**234**
11	One-Story	0.25826	0.84956	492	66	**558**	159	3	**162**
11	Townhouse	0.25826	0.84956	235	19	**253**	68	-3	**66**
12	Two-Story	0.15951	0.84956	444	49	**493**	131	-7	**124**
12	One-Story	0.15951	0.84956	257	58	**315**	79	3	**82**
12	Townhouse	0.15951	0.84956	131	16	**147**	37	-3	**35**
13	Two-Story	0.25826	0.84956	1044	31	**1076**	310	-4	**306**
13	One-Story	0.25826	0.84956	658	41	**699**	212	3	**215**
13	Townhouse	0.25826	0.84956	310	9	**320**	91	-1	**90**
15	Two-Story	0.1578	0.97875	1285	0	**1285**	430	0	**430**
15	One-Story	0.1578	0.97875	855	2	**857**	291	1	**292**
15	Townhouse	0.1578	0.97875	361	0	**361**	120	0	**120**

Table 40 – Annual Energy Cost Savings - Plenum Truss

Climate Zone	House Type	Utility Rate		Vs. Normal Leakage Base			Vs. Low Leakage Base		
		Elec. ($/kWh)	Gas ($/therm)	Electric ($)	Gas ($)	Total ($)	Electric ($)	Gas ($)	Total ($)
2	Two-Story	0.25826	0.84956	492	-5	**487**	129	-65	**64**
2	One-Story	0.25826	0.84956	257	45	**302**	61	-18	**43**
2	Townhouse	0.25826	0.84956	144	0	**144**	30	-21	**9**
3	Two-Story	0.25826	0.84956	552	-14	**539**	197	-39	**158**
3	One-Story	0.25826	0.84956	242	22	**264**	61	-8	**53**
3	Townhouse	0.25826	0.84956	144	-5	**139**	45	-17	**28**
5	Two-Story	0.25993	0.75708	640	-11	**629**	244	-19	**225**
5	One-Story	0.25993	0.75708	274	14	**288**	84	-1	**83**
5	Townhouse	0.25993	0.75708	152	-5	**147**	53	-12	**41**
6	Two-Story	0.25993	0.75708	944	-2	**942**	297	-2	**295**
6	One-Story	0.25993	0.75708	472	3	**475**	122	1	**123**
6	Townhouse	0.25993	0.75708	251	-2	**249**	76	-3	**73**
7	Two-Story	0.1578	0.97875	384	-6	**378**	120	-8	**112**
7	One-Story	0.1578	0.97875	180	8	**188**	46	1	**47**
7	Townhouse	0.1578	0.97875	116	-5	**111**	32	-6	**26**
8	Two-Story	0.25993	0.75708	716	-5	**711**	198	-10	**188**
8	One-Story	0.25993	0.75708	388	8	**396**	99	-1	**98**
8	Townhouse	0.25993	0.75708	213	-2	**211**	53	-5	**49**
9	Two-Story	0.25993	0.75708	792	-5	**788**	236	-9	**227**
9	One-Story	0.25993	0.75708	442	9	**451**	122	1	**123**
9	Townhouse	0.25993	0.75708	221	-3	**218**	61	-5	**56**
10	Two-Story	0.25993	0.75708	922	-5	**916**	244	-11	**232**
10	One-Story	0.25993	0.75708	525	10	**535**	137	0	**137**
10	Townhouse	0.25993	0.75708	251	-2	**249**	61	-6	**55**
11	Two-Story	0.25826	0.84956	764	9	**774**	189	-58	**131**
11	One-Story	0.25826	0.84956	454	48	**502**	121	-14	**107**
11	Townhouse	0.25826	0.84956	219	3	**222**	53	-19	**34**
12	Two-Story	0.15951	0.84956	421	3	**423**	107	-54	**54**
12	One-Story	0.15951	0.84956	238	42	**280**	61	-14	**47**
12	Townhouse	0.15951	0.84956	122	1	**122**	28	-18	**10**
13	Two-Story	0.25826	0.84956	961	-4	**957**	227	-40	**187**
13	One-Story	0.25826	0.84956	605	28	**633**	159	-9	**150**
13	Townhouse	0.25826	0.84956	280	-2	**278**	61	-12	**49**
15	Two-Story	0.1578	0.97875	1221	-1	**1220**	365	-1	**364**
15	One-Story	0.1578	0.97875	814	2	**816**	250	1	**251**
15	Townhouse	0.1578	0.97875	342	-1	**341**	102	-1	**101**

As was done previously with the energy savings, weighting factors based on housing starts were used to calculate sate average energy cost savings. These results are shown below in Table 41, along with the maximum savings value from any climate zone.

Table 41 – Weighted Average and Maximum Energy Cost Savings

Approach	House		Vs. High Leakage Base Elec. ($)	Gas ($)	Total ($)	Vs. Low Leakage Base Elec. ($)	Gas ($)	Total ($)
Cathedralized Attic	Two Story	Avg	780	-33	**748**	253	-56	**198**
		Max	1,202	-4	**1,198**	419	-4	**411**
	One Story	Avg	474	-6	**468**	170	-32	**138**
		Max	818	10	**814**	254	-5	**249**
	Townhouse	Avg	207	-15	**192**	73	-22	**51**
		Max	342	-3	**339**	114	-3	**105**
Dropped Ceiling	Two Story	Avg	752	21	**773**	226	-3	**223**
		Max	1,285	59	**1,285**	430	0	**430**
	One Story	Avg	444	29	**473**	140	4	**144**
		Max	855	69	**857**	291	7	**292**
	Townhouse	Avg	189	6	**196**	56	-1	**55**
		Max	361	20	**361**	120	0	**120**
Plenum Truss	Two Story	Avg	729	-3	**725**	202	-27	**175**
		Max	1,221	9	**1,220**	365	-1	**364**
	One Story	Avg	415	20	**435**	111	-5	**106**
		Max	814	48	**816**	250	1	**251**
	Townhouse	Avg	181	-2	**179**	48	-9	**38**
		Max	342	3	**341**	102	-1	**101**

CONCLUSIONS

Energy savings and energy cost savings that can be achieved by building houses with ducts in conditioned space are significant. The savings vary by the size of the house and by climate, although the approach used has less impact. One difference between the approaches is that the Cathedralized Attic and, to a lesser extent, the Plenum Truss approaches cause slight increases in heating energy. This is due to the increase in insulated envelope area that results from moving the insulation up to the roof (Cathedralized Attic) or up to an intermediate location between the attic floor and roof (Plenum Truss).

State wide energy impact results show that over a ten year period, programs promoting the construction of houses with ducts in conditioned space will save approximately 692,000,000 kWh over ten years, but increase gas consumption by 141,000 therms.

With cost increases to the builder of $0 to $1,000 for the dropped ceiling or cathedralized attic approaches ($2,000 to $4,000 for the plenum truss approach), paybacks can be less than one year for large houses, less than two years for smaller houses, and 3 to 5 years for townhouses. In severe climates, however, these paybacks will be much shorter, a year or less for all three house types. In mild climates, the payback period increase and certain approaches may no longer be cost effective. Table 42 shows the cost effectiveness of the approaches based on a less than 7 year payback to the home owner.

Table 42. Cost Effectiveness of Duct Placement Construction Approaches

Approach	Normal Leakage (22%)	Low Leakage (6%)
Cathedralized	Yes	Some Single Family No for Townhouses
Dropped	Yes	Most Single Family Some Townhouses
Plenum	Yes - some single family	Generally No

Additional research is needed to better understand the thermal performance of houses with ducts in conditioned space. In particular, the temperature behavior of the duct space over the course of the cooling and heating seasons and the dynamics of duct leakage into the conditioned duct space needs further investigation.

Appendix A
CBIA Data on Housing Starts

Housing Starts by Year and Region

Region	Clim. Zns.	Housing Type	1998	1999	2000	2001	2002
California Total	All	Single Family	96,137	102,168	104,158	106,668	122,053
		Multifamily	25,985	30,937	35,368	33,288	33,633
		Total	122,122	133,105	139,526	139,956	155,686
Bakersfield	13	Single Family	2,933	2,906	2,840	3,317	3,949
		Multifamily	410	230	165	93	40
		Total	3,343	3,136	3,005	3,410	3,989
Chico-Paradise	11	Single Family	909	1,013	978	1,009	1,160
		Multifamily	54	21	130	58	23
		Total	963	1,034	1,108	1,067	1,183
Fresno	13	Single Family	3,287	3,095	3,388	4,146	4,694
		Multifamily	1,698	393	299	196	497
		Total	4,985	3,488	3,687	4,342	5,191
Los Angeles	8/9	Single Family	6,613	7,656	8,304	8,268	8,168
		Multifamily	3,615	5,374	7,970	8,819	7,337
		Total	10,228	13,030	16,274	17,087	15,505
Merced	12	Single Family	1,023	1,023	1,329	1,101	1,574
		Multifamily	18	4	20	3	44
		Total	1,041	1,027	1,349	1,104	1,618
Modesto	12	Single Family	1,895	2,064	2,753	3,008	2,949
		Multifamily	123	41	177	147	155
		Total	2,018	2,105	2,930	3,155	3,104
Oakland	3	Single Family	7,125	8,811	7,589	6,344	7,737
		Multifamily	2,530	2,197	1,866	2,150	1,892
		Total	9,655	11,008	9,455	8,494	9,629
Orange County	6/8	Single Family	7,580	7,530	6,870	6,918	6,968
		Multifamily	2,705	3,970	5,311	4,051	4,778
		Total	10,285	11,500	12,181	10,969	11,746
Redding	11	Single Family	644	756	798	1,015	1,196
		Multifamily	42	25	83	4	122
		Total	686	781	881	1,019	1,318
Riverside	10	Single Family	16,773	18,784	18,915	23,186	29,868
		Multifamily	2,130	1,984	2,193	3,423	2,735
		Total	18,903	20,768	21,108	26,609	32,603
Santa Rosa	2	Single Family	2,127	2,357	2,052	1,743	1,442
		Multifamily	827	685	400	895	627
		Total	2,954	3,042	2,452	2,638	2,069
Sacramento	12	Single Family	10,032	10,430	12,194	13,465	16,328
		Multifamily	2,540	2,834	3,429	3,030	4,851
		Total	12,572	13,264	15,623	16,495	21,179
San Francisco	3	Single Family	1,832	1,697	1,842	1,055	976
		Multifamily	2,861	2,400	3,416	2,012	1,672
		Total	4,693	4,097	5,258	3,067	2,648
San Jose	4	Single Family	4,053	3,358	2,899	1,680	2,122
		Multifamily	3,485	3,313	3,437	3,897	2,502

		Total	7,538	6,671	6,336	5,577	4,624
Salinas	3	Single Family	1,215	1,498	1,512	927	1,030
		Multifamily	55	424	196	161	128
		Total	1,270	1,922	1,708	1,088	1,158
San Diego	7/10	Single Family	9,416	9,963	9,191	9,310	8,863
		Multifamily	2,566	5,394	5,947	5,462	4,600
		Total	11,982	15,357	15,138	14,772	13,463
St. Barara-St. Maria-Lompoc	6/5/5	Single Family	919	660	751	905	923
		Multifamily	97	132	93	62	674
		Total	1,016	792	844	967	1,597
Santa Cruz-Watsonville	3	Single Family	373	371	404	447	538
		Multifamily	128	234	205	324	202
		Total	501	605	609	771	740
San Luis Obisbo	5	Single Family	1,670	1,583	1,536	1,793	1,740
		Multifamily	53	80	98	260	273
		Total	1,723	1,663	1,634	2,053	2,013
Stockton-Lodi	12	Single Family	3,272	4,122	5,290	4,301	5,357
		Multifamily	110	5	25	308	312
		Total	3,382	4,127	5,315	4,609	5,669
Vallejo-Fairfield-Napa	3/12/2	Single Family	2,278	2,083	2,531	2,694	2,481
		Multifamily	315	726	176	921	1,144
		Total	2,593	2,809	2,707	3,615	3,625
Visalia-Tulare-Porterville	13	Single Family	1,441	1,562	1,523	1,651	1,861
		Multifamily	44	58	78	34	159
		Total	1,485	1,620	1,601	1,685	2,020
Yolo	12	Single Family	897	684	1,021	1,300	1,224
		Multifamily	504	690	194	67	96
		Total	1,401	1,374	1,215	1,367	1,320

The above data were then aggregated by climate zone. Regions which spanned multiple climate zones had their values evenly divided among the covered climate zones. The table below shows the results. The housing data above did not have any regions in climate zones 1, 14, 15 or 16. The difference between the California totals and the sum of the regional data were assigned, arbitrarily, to climate zone 15.

Housing Starts by Year and Climate Zone

CZ	Housing Type	1998	1999	2000	2001	2002
2	Single Family	2,886	3,051	2,896	2,641	2,269
	Multifamily	932	927	459	1,202	1,008
	Total	3,818	3,978	3,354	3,843	3,277
3	Single Family	11,304	13,071	12,191	9,671	11,108
	Multifamily	5,679	5,497	5,742	4,954	4,275
	Total	16,983	18,568	17,932	14,625	15,383
4	Single Family	4,053	3,358	2,899	1,680	2,122
	Multifamily	3,485	3,313	3,437	3,897	2,502
	Total	7,538	6,671	6,336	5,577	4,624
5	Single Family	2,283	2,023	2,037	2,396	2,355
	Multifamily	118	168	160	301	722
	Total	2,400	2,191	2,197	2,698	3,078
6	Single Family	4,096	3,985	3,685	3,761	3,792
	Multifamily	1,385	2,029	2,687	2,046	2,614
	Total	5,481	6,014	6,372	5,807	6,405
7	Single Family	4,708	4,982	4,596	4,655	4,432
	Multifamily	1,283	2,697	2,974	2,731	2,300
	Total	5,991	7,679	7,569	7,386	6,732
8	Single Family	7,097	7,593	7,587	7,593	7,568
	Multifamily	3,160	4,672	6,641	6,435	6,058
	Total	10,257	12,265	14,228	14,028	13,626
9	Single Family	3,307	3,828	4,152	4,134	4,084
	Multifamily	1,808	2,687	3,985	4,410	3,669
	Total	5,114	6,515	8,137	8,544	7,753
10	Single Family	21,481	23,766	23,511	27,841	34,300
	Multifamily	3,413	4,681	5,167	6,154	5,035
	Total	24,894	28,447	28,677	33,995	39,335
11	Single Family	1,553	1,769	1,776	2,024	2,356
	Multifamily	96	46	213	62	145
	Total	1,649	1,815	1,989	2,086	2,501
12	Single Family	17,878	19,017	23,431	24,073	28,259
	Multifamily	3,400	3,816	3,904	3,862	5,839
	Total	21,278	22,833	27,334	27,935	34,098
13	Single Family	7,661	7,563	7,751	9,114	10,504
	Multifamily	2,152	681	542	323	696
	Total	9,813	8,244	8,293	9,437	11,200
15	Single Family	7,830	8,162	7,648	7,085	8,905
	Multifamily	0	0	0	0	0
	Total	6,905	7,885	7,108	3,996	7,675

Appendix B
Results of DOE-2 Modeling by Climate Zone

Climate Zone	House Type	Configuration	Cooling Electric (kWh)	Total Electric (kWh)	Peak Electric (kW)	Total Gas (therms)
2	Two-Story	Low Leakage	5,157	27,190	8.9	419
2	Two-Story	High Leakage	6,534	28,597	9.7	489
2	Two-Story	Cath. Attic	4,424	26,458	8.7	557
2	Two-Story	Dropped Ceiling	4,571	26,633	8.5	426
2	Two-Story	Plenum Truss	4,629	26,692	8.6	495
2	One-Story	Low Leakage	2,871	15,675	5.3	437
2	One-Story	High Leakage	3,633	16,437	5.9	511
2	One-Story	Cath. Attic	2,403	15,207	5.1	499
2	One-Story	Dropped Ceiling	2,520	15,324	5.0	430
2	One-Story	Plenum Truss	2,608	15,441	5.1	458
2	Townhouse	Low Leakage	1,553	12,687	3.9	240
2	Townhouse	High Leakage	1,992	13,126	4.2	265
2	Townhouse	Cath. Attic	1,348	12,452	3.9	293
2	Townhouse	Dropped Ceiling	1,377	12,511	3.8	242
2	Townhouse	Plenum Truss	1,436	12,570	3.9	265
3	Two-Story	Low Leakage	5,713	27,688	8.2	261
3	Two-Story	High Leakage	7,061	29,065	8.8	291
3	Two-Story	Cath. Attic	4,454	26,399	8.0	352
3	Two-Story	Dropped Ceiling	5,069	27,073	8.0	265
3	Two-Story	Plenum Truss	4,922	26,926	8.0	307
3	One-Story	Low Leakage	2,901	15,646	4.8	282
3	One-Story	High Leakage	3,604	16,349	5.2	317
3	One-Story	Cath. Attic	2,256	14,972	4.6	329
3	One-Story	Dropped Ceiling	2,608	15,353	4.6	275
3	One-Story	Plenum Truss	2,666	15,412	4.6	291
3	Townhouse	Low Leakage	1,524	12,599	3.7	199
3	Townhouse	High Leakage	1,904	12,980	3.9	213
3	Townhouse	Cath. Attic	1,201	12,247	3.6	240
3	Townhouse	Dropped Ceiling	1,348	12,423	3.6	200
3	Townhouse	Plenum Truss	1,348	12,423	3.6	219
5	Two-Story	Low Leakage	6,182	28,216	8.0	180
5	Two-Story	High Leakage	7,677	29,739	8.5	191
5	Two-Story	Cath. Attic	4,776	26,780	7.8	237
5	Two-Story	Dropped Ceiling	5,508	27,512	7.7	181
5	Two-Story	Plenum Truss	5,274	27,278	7.8	205
5	One-Story	Low Leakage	3,076	15,822	4.6	213
5	One-Story	High Leakage	3,780	16,554	4.9	232
5	One-Story	Cath. Attic	2,403	15,148	4.5	246
5	One-Story	Dropped Ceiling	2,754	15,500	4.5	204
5	One-Story	Plenum Truss	2,754	15,500	4.5	214
5	Townhouse	Low Leakage	1,582	12,657	3.7	173
5	Townhouse	High Leakage	1,963	13,038	3.8	182
5	Townhouse	Cath. Attic	1,231	12,306	3.6	208
5	Townhouse	Dropped Ceiling	1,406	12,482	3.6	174
5	Townhouse	Plenum Truss	1,377	12,452	3.6	189

Climate Zone	House Type	Configuration	Cooling Electric (kWh)	Total Electric (kWh)	Peak Electric (kW)	Total Gas (therms)
6	Two-Story	Low Leakage	9,728	31,820	8.5	142
6	Two-Story	High Leakage	12,189	34,310	9.1	142
6	Two-Story	Cath. Attic	8,145	30,208	8.4	152
6	Two-Story	Dropped Ceiling	8,673	30,765	8.3	142
6	Two-Story	Plenum Truss	8,556	30,677	8.3	145
6	One-Story	Low Leakage	5,303	18,078	5.0	151
6	One-Story	High Leakage	6,622	19,426	5.4	154
6	One-Story	Cath. Attic	4,395	17,170	4.9	160
6	One-Story	Dropped Ceiling	4,747	17,551	4.9	148
6	One-Story	Plenum Truss	4,805	17,609	4.9	150
6	Townhouse	Low Leakage	2,520	13,566	3.7	145
6	Townhouse	High Leakage	3,164	14,240	3.9	146
6	Townhouse	Cath. Attic	2,080	13,126	3.7	157
6	Townhouse	Dropped Ceiling	2,256	13,302	3.6	145
6	Townhouse	Plenum Truss	2,227	13,273	3.7	149
7	Two-Story	Low Leakage	6,710	28,684	7.9	149
7	Two-Story	High Leakage	8,350	30,355	8.4	151
7	Two-Story	Cath. Attic	5,567	27,542	7.8	172
7	Two-Story	Dropped Ceiling	5,977	27,952	7.7	149
7	Two-Story	Plenum Truss	5,948	27,923	7.8	157
7	One-Story	Low Leakage	3,487	16,173	4.7	172
7	One-Story	High Leakage	4,307	17,023	5.0	179
7	One-Story	Cath. Attic	2,842	15,529	4.6	191
7	One-Story	Dropped Ceiling	3,076	15,793	4.5	167
7	One-Story	Plenum Truss	3,164	15,880	4.6	171
7	Townhouse	Low Leakage	2,022	13,068	3.6	145
7	Townhouse	High Leakage	2,549	13,595	3.8	146
7	Townhouse	Cath. Attic	1,699	12,745	3.6	159
7	Townhouse	Dropped Ceiling	1,817	12,833	3.6	145
7	Townhouse	Plenum Truss	1,846	12,863	3.6	151
8	Two-Story	Low Leakage	7,852	29,886	8.5	164
8	Two-Story	High Leakage	9,815	31,878	9.1	170
8	Two-Story	Cath. Attic	6,798	28,831	8.3	194
8	Two-Story	Dropped Ceiling	6,973	29,036	8.2	165
8	Two-Story	Plenum Truss	7,061	29,124	8.3	177
8	One-Story	Low Leakage	4,366	17,111	5.0	183
8	One-Story	High Leakage	5,420	18,224	5.5	194
8	One-Story	Cath. Attic	3,662	16,408	4.8	203
8	One-Story	Dropped Ceiling	3,838	16,613	4.7	178
8	One-Story	Plenum Truss	3,955	16,730	4.7	184
8	Townhouse	Low Leakage	2,373	13,419	3.8	152
8	Townhouse	High Leakage	2,959	14,035	4.0	155
8	Townhouse	Cath. Attic	2,051	13,097	3.7	168
8	Townhouse	Dropped Ceiling	2,110	13,156	3.7	152
8	Townhouse	Plenum Truss	2,139	13,214	3.7	158

Climate Zone	House Type	Configuration	Cooling Electric (kWh)	Total Electric (kWh)	Peak Electric (kW)	Total Gas (therms)
9	Two-Story	Low Leakage	8,438	30,501	9.3	162
9	Two-Story	High Leakage	10,548	32,640	10.2	168
9	Two-Story	Cath. Attic	7,266	29,358	8.5	192
9	Two-Story	Dropped Ceiling	7,413	29,534	8.3	163
9	Two-Story	Plenum Truss	7,501	29,593	8.4	174
9	One-Story	Low Leakage	4,776	17,551	5.3	185
9	One-Story	High Leakage	5,977	18,781	6.0	196
9	One-Story	Cath. Attic	4,014	16,818	4.8	206
9	One-Story	Dropped Ceiling	4,161	16,965	4.8	179
9	One-Story	Plenum Truss	4,278	17,082	4.8	184
9	Townhouse	Low Leakage	2,432	13,507	4.1	150
9	Townhouse	High Leakage	3,076	14,122	4.3	152
9	Townhouse	Cath. Attic	2,110	13,185	3.8	167
9	Townhouse	Dropped Ceiling	2,168	13,243	3.8	150
9	Townhouse	Plenum Truss	2,197	13,273	3.8	156
10	Two-Story	Low Leakage	9,903	32,025	9.4	171
10	Two-Story	High Leakage	12,511	34,632	10.3	179
10	Two-Story	Cath. Attic	8,761	30,911	9.4	209
10	Two-Story	Dropped Ceiling	8,819	30,970	9.1	171
10	Two-Story	Plenum Truss	8,966	31,087	9.3	186
10	One-Story	Low Leakage	5,801	18,635	5.7	193
10	One-Story	High Leakage	7,296	20,129	6.3	206
10	One-Story	Cath. Attic	5,040	17,873	5.4	217
10	One-Story	Dropped Ceiling	5,127	17,961	5.2	187
10	One-Story	Plenum Truss	5,245	18,107	5.3	193
10	Townhouse	Low Leakage	2,754	13,859	4.1	160
10	Townhouse	High Leakage	3,487	14,591	4.3	165
10	Townhouse	Cath. Attic	2,461	13,536	4.0	181
10	Townhouse	Dropped Ceiling	2,461	13,566	3.9	160
10	Townhouse	Plenum Truss	2,520	13,624	4.0	168
11	Two-Story	Low Leakage	8,497	30,677	10.4	458
11	Two-Story	High Leakage	10,724	32,904	11.8	537
11	Two-Story	Cath. Attic	7,618	29,827	9.8	596
11	Two-Story	Dropped Ceiling	7,559	29,739	9.6	467
11	Two-Story	Plenum Truss	7,764	29,944	9.7	526
11	One-Story	Low Leakage	5,127	18,049	6.0	440
11	One-Story	High Leakage	6,446	19,338	7.0	514
11	One-Story	Cath. Attic	4,483	17,375	5.6	516
11	One-Story	Dropped Ceiling	4,512	17,433	5.5	436
11	One-Story	Plenum Truss	4,659	17,580	5.6	457
11	Townhouse	Low Leakage	2,490	13,654	4.4	236
11	Townhouse	High Leakage	3,164	14,298	4.7	261
11	Townhouse	Cath. Attic	2,227	13,390	4.2	288
11	Townhouse	Dropped Ceiling	2,227	13,390	4.1	239
11	Townhouse	Plenum Truss	2,285	13,449	4.2	258

Climate Zone	House Type	Configuration	Cooling Electric (kWh)	Total Electric (kWh)	Peak Electric (kW)	Total Gas (therms)
12	Two-Story	Low Leakage	7,413	29,534	9.7	409
12	Two-Story	High Leakage	9,376	31,497	10.7	475
12	Two-Story	Cath. Attic	6,505	28,626	9.2	537
12	Two-Story	Dropped Ceiling	6,592	28,714	9.1	417
12	Two-Story	Plenum Truss	6,710	28,860	9.2	472
12	One-Story	Low Leakage	4,307	17,170	5.6	404
12	One-Story	High Leakage	5,420	18,283	6.4	469
12	One-Story	Cath. Attic	3,662	16,525	5.3	475
12	One-Story	Dropped Ceiling	3,809	16,672	5.2	401
12	One-Story	Plenum Truss	3,926	16,789	5.3	420
12	Townhouse	Low Leakage	2,197	13,331	4.1	226
12	Townhouse	High Leakage	2,783	13,917	4.4	248
12	Townhouse	Cath. Attic	1,934	13,068	4.0	275
12	Townhouse	Dropped Ceiling	1,963	13,097	4.0	229
12	Townhouse	Plenum Truss	2,022	13,156	4.0	247
13	Two-Story	Low Leakage	10,841	33,050	10.2	306
13	Two-Story	High Leakage	13,624	35,892	11.8	348
13	Two-Story	Cath. Attic	9,815	32,083	9.4	398
13	Two-Story	Dropped Ceiling	9,610	31,849	9.2	311
13	Two-Story	Plenum Truss	9,903	32,171	9.3	353
13	One-Story	Low Leakage	6,651	19,572	5.9	317
13	One-Story	High Leakage	8,350	21,301	6.8	361
13	One-Story	Cath. Attic	5,831	18,752	5.4	366
13	One-Story	Dropped Ceiling	5,801	18,752	5.3	313
13	One-Story	Plenum Truss	6,006	18,957	5.4	328
13	Townhouse	Low Leakage	3,223	14,357	4.3	191
13	Townhouse	High Leakage	4,073	15,207	4.8	203
13	Townhouse	Cath. Attic	2,930	14,093	4.1	225
13	Townhouse	Dropped Ceiling	2,871	14,005	4.0	192
13	Townhouse	Plenum Truss	2,959	14,122	4.0	205
15	Two-Story	Low Leakage	19,074	41,606	10.7	140
15	Two-Story	High Leakage	24,524	47,026	13.4	140
15	Two-Story	Cath. Attic	16,789	39,408	10.1	144
15	Two-Story	Dropped Ceiling	16,261	38,881	9.8	140
15	Two-Story	Plenum Truss	16,672	39,291	10.0	141
15	One-Story	Low Leakage	11,632	24,700	6.2	143
15	One-Story	High Leakage	15,207	28,274	7.8	144
15	One-Story	Cath. Attic	9,991	23,088	5.9	148
15	One-Story	Dropped Ceiling	9,728	22,854	5.8	142
15	One-Story	Plenum Truss	10,021	23,117	5.9	142
15	Townhouse	Low Leakage	5,391	16,584	4.4	141
15	Townhouse	High Leakage	6,944	18,107	5.3	141
15	Townhouse	Cath. Attic	4,717	15,939	4.2	144
15	Townhouse	Dropped Ceiling	4,600	15,822	4.1	141
15	Townhouse	Plenum Truss	4,717	15,939	4.2	142

Code Officials Technical Information Package

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Integrated Energy Systems
Productivity and Building Science

On behalf of the:
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Public Interest Energy Research (PIER) Program

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Integrated Design of Residential Ducting and Airflow Systems

Roger Hedrick

GARDAnalytics
Energy, Economic and Environmental Research

New Buildings Institute

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Project Director: Roger Hedrick, GARD Analytics, Inc.

Technical Assistance: Geof Syphers, XENERGY; Rob Hammon, Con-Sol; Bill Irvine, BCI Testing.

Review and Advisory Committee: Rick Chitwood, Chitwood Energy Management; Iain Walker, Lawrence Berkeley National Laboratory; Joe Lstiburek, Building Science Corporation; Bruce Wilcox, Berkeley Solar Group; Jamie Lyons, National Association of Home Builders Research Center; Marshall Hunt, Pacific Gas and Electric.

Project Management: Cathy Higgins, Program Director for the New Buildings Institute and Don Aumann, Contract Manager for the California Energy Commission.

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ABOUT PIER

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission, annually awards up to $62 million to conduct the most promising public interest energy research by partnering with research, development and demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

1. Buildings End-use Energy Efficiency
2. Industrial/Agricultural/Water End-use Energy Efficiency
3. Renewable Energy
4. Environmentally Preferred Advanced Generation
5. Energy-Related Environmental Research
6. Strategic Energy Research.

This project contributes to #1 above, the PIER Buildings Program Area and is a part of the PIER final report (publication #P500-03-082). For more information on the PIER Program, please visit the Commission's Web site at: www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200. For other public reports within the *Integrated Energy Systems — Productivity and Building Science* project, please visit www.newbuildings.org/PIER

LEGAL NOTICE

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OBJECTIVES

This report provides technical information to specific audiences regarding building houses with ducts in conditioned space. In particular, the report provides information intended for code officials regarding roof venting issues, and information for consumers on the costs and benefits of houses with ducts in conditioned space. Both sets of information are intended to address market barriers identified earlier. One of these barriers is that building houses with the cathedralized attic approach violates building code requirements for venting of the roof deck. Another is the lack of consumer demand for houses with ducts in conditioned space, due to lack of familiarity with the concepts and their impact on the cost and energy consumption of their new house.

INTRODUCTION

New houses in California typically are built with the air handler and ductwork located in the unconditioned attic. The ductwork is commonly built with ductboard plenums and flex duct, insulated to R4.2, or sometimes R6 (code requirement is R4.2). In recent years, numerous studies have found large energy losses from these systems, primarily due to air leaks in the air handler and duct system, but also including heat conducted through the duct material. These losses are especially deleterious in the summer when solar radiation can elevate the attic temperature well above the outdoor air temperature. Previous studies have found that typical duct systems can lose as much as 40% of the space conditioning energy consumed by the HVAC system.

Air leaks on the supply side of the system are lost to the unconditioned attic and eventually to the outdoors, while leaks on the return side result in unconditioned air being brought into the system, increasing the space conditioning load. Unbalanced leakage (for example, large supply leaks with small return leaks) can significantly affect the air pressure in the house resulting in increased infiltration and the corresponding increase in space conditioning loads. Leakage can also cause comfort problems by reducing supply air flow to the house or to individual rooms, and by increasing infiltration.

The problem of duct leakage has primarily been addressed through a variety of programs aimed at reducing leakage in the duct system. These include several utility company programs which provided training to duct installers followed by duct leakage testing. The Title 24 ACM manual now includes a credit for ducts with tested leakage below 6% of system airflow. These programs have reduced typical duct leakage in new construction, but few builders take advantage of the Title 24 energy credit. It is believed that typical duct leakage values are now around 20% to 25% of system airflow. And, ducts are still located in the unconditioned attic where the leaks and thermal conduction is lost to the outdoors.

Placing ducts inside conditioned space requires changes from conventional building practice in a number of areas. It is expected that as homes are built with ducts in conditioned space, that problems will be identified and opportunities for improved methods developed.

To date, relatively few homes have been built with ducts in conditioned space. An exception to this statement is homes with systems in basements, common in northern climates. In California, however, most homes are built with a slab on grade, and the duct system in the attic. Pulte Homes, working with the USDOE Building America Program, has been building homes in Arizona, Nevada and now California, putting the ducts and air handler in an Unvented Conditioned Attic. A few homes have also been built using the Dropped Ceiling approach, mostly in the southeast, again in cooperation with Building America. Finally, some homes have been built in the Shasta, California area with insulation and HVAC work done by Rick Chitwood, using Dropped Ceilings.

MARKET BARRIERS

Market barriers are issues which prevent California homes from being built with ducts in conditioned space. A previous report, Deliverable 6.4.2b, *Market Barriers - Identification and Approaches to Overcome Them,* identified a number of barriers. This report is intended to provide information that can be used by the builder or the CEC to address two of these issues. They are:

- Code Conflicts
- Consumer Demand/Additional Cost

The first of these, Code Conflicts, has to do with the requirement in most building codes, that roof decks be vented. The Cathedralized Attic approach to building ducts in conditioned space directly conflicts with this requirement, as the roof deck is used as the primary air barrier, with the insulation installed immediately below that. This requires that openings through the roof deck be avoided and sealed when unavoidable. Ridge vents, eave vents, etc., are not installed, and penetrations for plumbing vents, exhaust fan outlets, etc., are tightly sealed to the roof deck.

The second has to do with builders being driven by consumer demand when determining what features to include in new houses. The surest way for a feature to become widely incorporated into new housing is for consumers to ask for and be willing to pay for that feature. This can only happen, however, if consumers are aware of the feature and its benefits.

The following section of this report addresses the Code Conflicts market barrier and is intended to be distributed to code officials, presumably in the form of a stand-alone white paper. A separate tri-fold brochure has been produced that addresses the Consumer Demand market barrier.

INFORMATION FOR CODE OFFICIALS RELATED TO HOUSES WITH CATHEDRALIZED ATTICS

This section discusses the use of an unvented roof deck as part of the "Cathedralized Attic" approach to building houses with ducts inside conditioned space. This approach may also be known by other names, such as "unvented, conditioned attic."

Building Code Official's Briefing Document
Variance for Attic Venting due to "Cathedralized Attic"

Code Requirement

Most building codes require that attics be ventilated. The technical basis for the code requirement is based on three issues:

- Attic venting limits condensation of moisture from warm indoor air on cold roof surfaces.
- Prevent ice dam formation.
- Lower the temperature of roofing materials in hot climates.

A cathedralized attic approach to building a house with ducts in conditioned space involves using the roof deck as the primary air barrier, with the insulation installed immediately below that. This requires that openings through the roof deck be avoided and sealed when unavoidable. Ridge vents, eave vents, etc., are not installed, and penetrations for plumbing vents, exhaust fan outlets, etc., are tightly sealed to the roof deck.

Most building codes require that attics be ventilated. Building a house with the cathedralized attic approach would not comply with the venting requirement. This document discusses the issue, including information on the technical basis for the requirement, climatic limitations on when attic venting is or is not required, and options for the builder to address the issue in cold climates.

CODE VARIANCE

The issues of condensation, ice dam formation and roofing material temperature can be successfully addressed without attic venting. Attic venting is not required provided alternatives are used that address all of the code requirement issues.

Numerous developments built using the cathedralized attic approach have been successfully completed. These have primarily been in hot dry climates, including Las Vegas; Tucson and Phoenix, AZ; and Tracy and Banning, CA. There have also been some developments built in hot humid climates, including Georgetown, TX and Ft. Myers, FL. The success of the development in Banning, CA has led the neighbroing town of Beaumont, CA to grant a variance to allow construction of a similar development there. Pulte Homes, in particular, have had great success with the approach and have included it in more than a dozen different developments.

Issue - Cold Climate Condensation

Description of Problem

When the outdoor temperature is low, and insulation is located at the attic floor, the roof assembly can be assumed to be at or near the outdoor temperature. Conditioned indoor air will often have a dewpoint above this temperature. For example, if the indoor temperature is 72°F with 30% relative humidity, the dewpoint is 39°F. When the outdoor temperature is below this temperature, indoor air leaking into the attic will result in condensation on the underside of the roof deck. Attic venting serves to circulate this indoor air to the outside before condensation occurs, and serves to remove moisture that does condense.

Alternative Solution

When a house is built with ducts in a conditioned Cathedralized Attic, the insulation is moved to the underside of the roof. The air barrier, however, will be above the insulation at the underside of the roof deck. This surface will be cold, and condensation will occur if measures are not taken to avoid it. The recommended measure is to add insulation above the roof deck, between the roofing and the roof deck. This insulation will have a temperature gradient through its depth, serving to maintain the inside of the roof deck at a higher temperature.

The insulation design is based on maintaining the underside of the roof deck at a monthly average temperature of 45°F or more for the coldest month of the year. 45°F corresponds to the dewpoint of air at 71°F with 40% RH. The monthly average is used because while there will be short term excursions of the roof temperature below 45°°F, there will be corresponding swings above 45°F. Condensation which occurs during the cold periods will be evaporated during the warm periods. Typical building materials have sufficient hygric buffer capacity to tolerate occasionally being wetted when the dewpoint exceeds the material temperature by a small amount. For additional information on this topic, see “Unvented Roof Systems” at www.buildingscience.com/resources/roofs/default.htm.

Mold growth occurs when materials are wet for an extended period, which is not the case here.

The amount of insulation to be installed above the roof deck is determined by using the following procedure:

- Find the lowest monthly average temperature for your location (for example, weather.com for a particular location has "averages and records" that provides monthly average temperatures). Note: this is <u>not</u> the monthly average low temperature, but the overall average temperature for the coldest month.
- If this temperature is below 45°F, subtract this temperature from the heating indoor temperature. For example, Grass Valley, CA has a January average temperature of 40°F, which gives a temperature difference of 30°F (70°F – 40°F).
- Subtract the coldest monthly average outdoor temperature from the target roof deck temperature (45°F – 40°F = 5°F).
- Divide this result by the indoor – outdoor temperature difference (5°F / 30°F = 0.17).
- Multiply this ratio by the overall R-value required for the roof to find the minimum R-value that is needed above the roof sheathing. For example, if total ceiling insulation of R-38 is required, the rigid insulation above the roof sheathing will be at least R-6.5 (38 x 0.17 = 6.46), with R-31.5 insulation under the roof deck.
- If the interior insulation is increased, the exterior insulation must be increased as well, such that the ratio of the exterior R-value to the total insulation R-value is at least 0.17.
- Check with the structural engineer or truss supplier that the insulation and additional sheathing layer are acceptable.

When insulation is installed above the roof deck in the manner described above, significant condensation on the underside of the roof deck should be avoided, and the need for attic venting to prevent the problem will be eliminated.

Issue – Ice Dam Prevention

Description of Problem

Ice dams are caused when heavy snow accumulates on a roof, and the surface temperature of the roof, under the snow, is allowed to exceed freezing temperature due to heat loss through the attic. When this occurs, the bottom of the snow layer begins to melt, and runs down the slope of the roof. As it reaches the eaves where there is no attic heat, water refreezes forming the ice dam. As more and more water runs down to the dam, the water can back up and leak through the roofing. Water damage can be significant when this occurs.

Alternative Solution

Modern roofing design is aimed at avoiding the warm roof which creates the melting that leads to the ice dam. This is primarily achieved through sufficient roof insulation, minimizing heat transfer into the snow. Recent research has shown that attic venting is necessary only in the coldest climates with heavy snowfalls (see *Venting of Attics and Cathedral Ceilings*, Rose and TenWolde, ASHRAE Journal, October 2002, page 26). The authors cite a study that shows that with R-20 roof insulation and no attic venting, ice dams should be avoided in Philadelphia, Washington DC, and Chicago. In Madison, Boston and Sioux Falls, R-30 insulation without venting is acceptable. In Minneapolis and Portland, Maine, the requirement increases to R-40. In Marquette, Michigan and Bangor, Maine attic venting is required to avoid ice dam problems, regardless of the amount of roof insulation.

Given that the California Energy Code requires R-39 roof insulation in all cold climates, ice dam formation with unvented attics does not appear to be a significant concern. Attic venting should not be required when adequate roof insulation is properly installed.

Issue – Overheating of the Roof Assembly

Description of Problem

Attic venting during cooling conditions serves to provide a means of removing heat from the roof assembly. The roofing is heated through the absorption of solar radiation. This heating results in transfer of heat into the outside air through convection, and conduction through the roof deck for eventual convection into the attic air. If the attic is unvented, the temperature will rise higher in the attic because the warmed air is not removed, slowing heat transfer from the roofing and increasing their temperature. The warmer attic will also increase the load on the cooling system.

Alternative Solution

The increased temperature experienced by the roofing will cause problems for asphalt shingles. Most shingle manufacturers' warrantees require that the roofing be vented. To avoid these problems, it is recommended that asphalt shingles not be used with a Cathedralized Attic. Tile or shake roofing should be used. Homes are currently being built successfully in Arizona; Las Vegas, NV; and Banning, CA, with unvented attics with tile roofs. The modest temperature increases expected in the roofing materials with unvented attics do not affect the life of tile or wood shake roofs.

Due to the increased roofing temperature, there is also an increase in cooling loads with unvented attics. Some research, however, has found that the load increase to be so small as to be negligible. In any case, the increase in load is more than offset by the increased efficiency of the HVAC distribution system when it is installed in conditioned space. As long as appropriate roofing materials are used, attic venting should not be required in hot climates.

BACKGROUND INFORMATION - HOUSES WITH CATHEDRALIZED ATTICS

The "Cathedralized Attic" approach to building ducts in conditioned space involves relocating the air and thermal barrier from the typical location at the attic floor to the underside of the roof deck. This approach may also be known by other names, such as "unvented, conditioned attic." The HVAC system and ductwork are then installed as usual in the attic, but this space is now inside the air and thermal barrier.

In order to have the roof deck provide a high quality air barrier, typical ridge and eave or soffit vents are not installed. Seams between roof decking material are sealed by the roofing paper, with caulking or insulating foam used to seal around roof penetrations. The roof is sealed to the top of the exterior walls to provide a continuous air barrier. See Figure 1 for one example of how this is done.

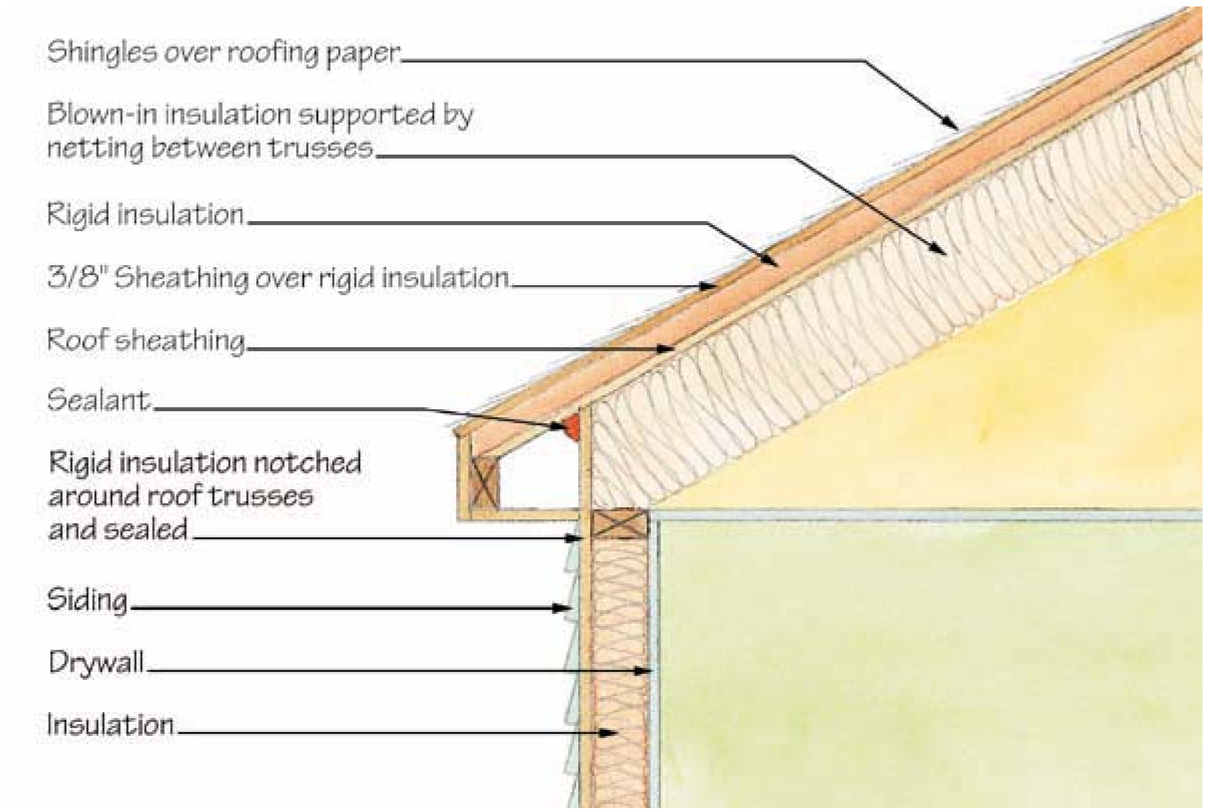

Figure 1 - Insulation and Sealing of Cathedralized Attic Roof

Using the Cathedralized Attic approach to build houses with ducts inside conditioned space can save significant amounts of energy, particularly electricity for cooling, compared to duct sealing alone. The savings depend on climate, but are typically 10% to 22% of total cooling system electricity consumption.

For more information on building houses with the ducts inside the conditioned space, please visit www.energy.ca.gov/pier/buildings.